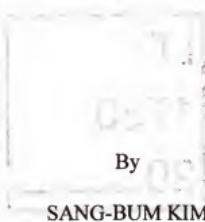


TIMING CONTROL OF ONE-HANDED CATCHING:
BALL ACCELERATING BY GRAVITY



A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
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**TIMING CONTROL OF ONE-HANDED CATCHING:
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Tau is defined as the inverse of the relative rate of dilation of an approaching object's image on the retinal plane of the observer. The use of tau for the interceptive timing control has been supported by empirical data. However, recent studies and reviews have identified incongruent evidence, indicating that the interceptive timing action may involve more than the optical variable tau. The aim of Experiments 1 and 2 was to determine the extent that tau can be used as a control variable source of visual information and examine whether additional visual information sources affect an interceptive timing task in a gravitational acceleration context.

In Experiment 1, a one-handed ball catching task with different ball drop heights and ball sizes was tested in a totally dark room condition with only right eye monocular vision available. Participants had to rely only on an optical expansion image (tau) of the luminescent dropping ball. However, in Experiment 2, vision (binocular versus monocular vision) and environment (illuminated versus totally dark room) conditions were manipulated in the one-handed ball catching task.

The results of both experiments showed that tau was used for catching a ball only when the approaching ball was visible in the monocular vision combined with the dark room condition. When binocular vision was available in an illuminated environment, (a) the catching performance scores were significantly increased, and (b) the index finger and thumb movements of the catching hand were more precise and consistent than in the monocular and dark environment conditions.

These findings suggest that the human control system for interceptive timing actions can use a minimal amount of visual information to catch a ball under the restricted conditions based on the optical expansion rate of the approaching ball. However, when multiple sources of visual information such as binocular vision and/or an illuminated room are available, the human control system uses these multiple sources simultaneously to achieve more accurate and consistent catching actions. Overall, the results infer that the visual motor control system is flexible and with multiple processing pathways to achieve optimal performance.

CHAPTER 1 INTRODUCTION AND REVIEW OF LITERATURE

Introduction

When hitting or catching a ball, performers need to time the event precisely so that they can be in the right place at the right time. In sports like baseball or cricket, the temporal precision required to hit a home run or a six is \pm 2 to 4 ms (Regan, 1992). Temporally coordinating movements with external events to this level of precision requires accurate and reliable anticipatory timing information. These types of timing movements are generally based on visual information about the time remaining until the object reaches the performer (Lee, 1980; Turvey & Carello, 1986).

A specific type of visual information known as tau may be used directly to specify time-to-contact of an impending collision with an object or surface in the environment. This optic variable is defined as the inverse of the relative rate of dilation of an approaching object's image on the retinal plane of the observer (Lee, 1976). Frequently, this explanation is referred to as the tau-hypothesis.

Theoretically, tau is visually available and does not involve prior measurement of object speeds, distance, or acceleration, and requires no complex computation. This approach postulates that information required for accurate perception of the world is entirely present in the stimulus so that the additional information from memory or other constructive processes is unnecessary (Gibson, 1961; Turvey & Carello, 1986). The use of tau has been supported by a body of empirical data. Lee and Raddish (1981) reported evidence that tau is the basis for the timing of wing retraction in diving gannets, as well

as ball-punching from a vertical ball drop (Lee et al., 1983). Furthermore, tau has been implicated in the timing of leg extension in landing house flies (Wagner, 1982) and hawks (Davies & Green, 1990), ball hitting (Bootsma & van Wieringen, 1990), and ball catching (Savelsbergh et al., 1991, 1993). Psychological experiments have confirmed that human observers are sensitive to tau (Kaiser & Mowafy, 1993; Regan & Hanstra, 1993), and electrophysiological studies have identified neurons that are sensitive to $1/\tau$ in the optic tectum of pigeons (Wang & Frost, 1992; Sun & Frost, 1998). These findings and subsequent arguments suggest a simple explanation of how interceptive timing behaviors are made.

However, recent studies and reviews have identified incongruent evidence; thus, criticisms of the tau hypothesis are mounting (Lacquaniti, Carozzo, & Borghese, 1993; Tresilian, 1990, 1993, 1994, 1999; Wann, 1996). Tresilian (1994, 1995, 1999) argued that tau-based explanations have a deceptive simplicity. Based on critical analysis of previous empirical data, temporal precision requirements of interceptive timing action have revealed that tau-based explanations for interceptive timing tasks are not fully valid. For example, given that tau hypothesis is based on a constant-velocity approach, the estimate of actual time-to-contact, provided by tau (the inverse of the relative rate of retinal expansion) can only be exact when the rate of approach between the observer or actor and the approaching object or surface is constant. However, constant approach velocities are rare in nature. Thus, tau-based estimates of time-to-contact should not necessarily contain accuracy in timing. Specifically, when an object is accelerating toward an observer (or vice versa), tau will over-estimate actual time-to-contact whereas under

conditions of deceleration tau will underestimate actual time-to-contact (Tresilian, 1991, 1995, 1999; Wann, 1996).

Despite these limitations of the tau-based explanation, there has been a paucity of studies investigating whether tau can be used in an accelerative condition when an object approaches directly to the performer who is asked to intercept or catch it (Lee & Reddish, 1981; Lee, Young, Reddish, Lough, & Clayton 1983). Specifically, no studies have been conducted in a gravitational acceleration condition with direct control of visual depth or distance perception variables. If catching tasks were performed in normal, full light conditions, the catching performance could be achieved by multiple resources of visual information such as absolute and/or relative disparity. Thus, isolating potential confounding variables to catching performance would be difficult in a lighted context. However, in a totally dark room condition, in which only a luminescent ball is visible with fixed drop distances and ball sizes, the human perceptual system can easily adapt and can use perceptual anticipation processes based on earlier trials (Trisilian, 1997). An additional limitation of previous studies is that most studies have examined only one aspect of performance, such as performance score (e.g., success or failure of a catch), a button-press task to determine the initiation of a reaction, and perceptual judgement of information on a computer screen. These approaches fail to provide the continuous perception-action couplings of interceptive actions (Tresilian, 1995; Williams et al., 1999). Therefore, the conflicting results and subsequent scientific debate may be caused by a failure of continuous online visual information, such as the expansion rate of retinal image as a ball approaches during the execution of catching. A further complication involves the superficial analysis of the interceptive actions. Detailed kinematics about the

catching hands as well as the approaching ball are missing in the literature. Thus, to verify the priority of tau-based strategy for interceptive timing skill, a more systematic approach must be undertaken to control for possible confounding effects (variables).

Given the scientific debate surrounding tau, a tau-based strategy for interceptive timing skill arises from studies in which monocular versus binocular conditions are compared. Based on a tau assumption, if time-to-contact information is picked up directly from optical 'looming', as proposed by Lee (1976), then this information should be equally accessible to one eye as to two eyes, and coincidence-timing performance under monocular and binocular conditions should be equivalent. However, conflicting results have been reported for monocular versus binocular viewing (monocular versus binocular issues). McLeod et al. (1986) investigated time-to-contact while comparing binocular and monocular viewing conditions. They argued that if time-to-contact information were dependent on the pre-existence of distance information, performance on coincidence-timing tasks should be impaired if participants are required to perform the task monocularly rather than binocularly. The first task consisted primarily of temporal uncertainty. Performance, as assessed from the percentage of successful hits, was not significantly different between the monocular and binocular viewing conditions. A binocular advantage was found on the second task containing both spatial and temporal uncertainty. Mcleod et al. concluded that information about binocular displacement plays an essential role in the judgment of the direction of object flight but is non-essential for the judgment of time-to-contact. However, a comparison between only temporal uncertainty versus both spatial and temporal uncertainty may be unjustified given the

uncoupling of the natural links between perception and action during button-pressing (Bootsma, 1989; von Hofsten, 1987).

Similar research was attempted by Abernethy and Crassini (1989) using a coincidence-timing task in which absolutely no spatial uncertainty existed. Light emitting diodes' motion of between 2.24 m/s and 8.94 m/s was presented to participants over a 4.30 m runway and they were required to make a thumb-press response to coincide with the arrival of the light at the end of the runway. The response accuracy findings were consistent with those of McLeod et al. (1986); equivalent coincidence-timing accuracy (absolute error) and consistency (variable error) were obtained over monocular and binocular viewing conditions. However, under the monocular viewing condition, participants consistently made more late responses than during binocular viewing. The authors suggested that deprivation of binocular disparity information caused participants to slightly but systematically overestimate time-to-contact.

More recent work by von Hofsten et al. (1992) indicated consistent results with the previous studies, in that catching performance under a binocular condition was superior to that under a monocular condition. However, these studies did not examine the kinematics of the required movement, but rather used accuracy or performance scores (only one aspect of visuomotor performance). This result is not conclusive for determining the relative importance of monocular versus binocular vision.

In addition, the comparison of catching performance under binocular and monocular viewing conditions in full light conditions may be unreliable because relative and absolute distance perception information is available. Therefore, verifying a tau-based strategy used for interceptive timing control is difficult by comparing binocular and

monocular viewing conditions under the full light condition. To verify whether a tau-based strategy is used for timing control of interceptive skill, the comparison between full light and dark room (e.g., only the approaching ball is visible) conditions with binocular and monocular vision is necessary. Furthermore, a detailed kinematic analysis of catching movement should be required to look at multiple aspects of catching performance.

Review of Literature

Many daily experiences are dependent on visual information, especially judgment of coincidence timing. Judgments can be made to intentionally either avoid or engineer collisions with other objects or surfaces in the environment. Similar visual information may be used to produce coincidence, such as when striking or catching a fast moving ball.

When striking or catching a ball, accurate movements usually need to be precisely timed so that performers are in the right place at the right time to make successful hits or catches. Sports skills require precise coincidence-timing for highly skilled performance. Ball games require the ability to produce extremely accurate coincident-timing behavior required by a motor response coinciding with the arrival of an object at a designated point in space and time (Ripoll & Latiri, 1997). Mcleod et al. (1986) argued that in catching or striking a ball, motor response accuracy is determined by a temporal window defined by the equation: time window = (width of captor + diameter of the ball)/velocity of the ball. This temporal window for a successful hit or a catch can be as small as 10 ms in ball games such as baseball, cricket, or table tennis (Bahill & LaRitz, 1984; Bootsma & van Wieringen, 1990; Glencross & Cibich, 1977). For instance, Tresilian (1993) reported that for a ball dropped from a height of 1 m, arriving at the interception point with velocity equal to 4.4 m/s, that is to be contacted with an effector surface area of 10 cm, the

temporal window would be 22 ms. McLeod et al. (1986) varied the size of the bats used for interception and found that participants were capable of hitting a ball in a temporal window range of 5-10 ms.

Additionally, Regan (1986) demonstrated how cricket batsmen often have only 230 ms to cope with late fluctuations in the flight of a ball approaching at 150 km per hour (km/h). The temporal precision to hit a home run or a six is about ± 2 ms (Regan, 1992). Moreover, top level table tennis players showed typical values for timing variability in the ± 2.03 and ± 4.72 ms range by calculating the variability in timing the initiation of an attacking forehand drive (Bootsma & van Wieringen, 1990).

The main question from these coincident timing examples is how skilled performers produce movement so as to match the spatiotemporal constraints imposed on their behavior. More specifically, this question can be divided into two subcategories: (a) What mechanism is involved in visual information processing? Or, what kinds of visual information do skilled performers perceive from highly dynamic and complex environments to perform such exquisitely timed and consistent actions? and, (b) How fast can the performer perceive and process relevant visual information from the external environment?

Since the 1960's, the information processing models have dominated experimental psychology. The emphasis on sequential, independent stages in human performance has dictated a research strategy of reductionism, based largely on the recording of reaction time data. The principal intent within the information processing model has been to discover the nature of processing within schematic processing stages rather than the nature of the links between processes. Studies of perception have

generally involved tasks in which the responses required are simplistic and atypical motor actions (e.g., verbal reports, categorical judgments, or key press responses). Moreover, studies of movement control have been typically restricted to laboratory paradigms in which perceptual requirements of tasks are deliberately simplified to the point of being non-representative of real world skills. With the recent burgeoning of interest in ecological psychology, arising from the influential work of Gibson (1966, 1979), there has been a growing interest in the study of natural skills and a deliberate focus upon coincidence timing as a window to understanding the normal functional coupling and interaction between perception and action. The ecological significance of coincidence-timing skills has resulted in the recent examination of perception-action coupling in a diverse range of human and animal activities. However, despite this recent research emphasis, relatively little is known about how visually-guided coincidence timing skills are performed.

Visual perception and action research is undergoing a fundamental debate concerning the relationship between perception and action. There are two main perspectives: (a) the ‘cognitive’ and (b) the ‘ecological.’ Most of the current controversy has focused on the relative contribution of both the perceiver and the stimulus during perception of the environment.

Cognitive Perspective: Visual Perception and Action

The cognitive perspective has dominated experimental psychology with an emphasis on sequential and independent stages of human processing. This perspective assumes that information in the environment is perceived as cues, and then the cued information is elaborated by hypothetical internal processes (Davids et al., 1994; Schmidt

& Lee, 1999). The principal intent of this research has been to discover the nature of processing within processing stages rather than the nature of the links between processes.

Historically, the cognitive perspective approach was regarded as the establishment approach (Fodor & Pylyshyn, 1981), based on the internal representative structure with processing stage and a large role for internalized knowledge structures of movement. Thus, the persistence and change in movement behavior was explained through the use of representations of commands for an action. Feedback loops ensured that the action was sensitive to sudden changes in dynamic environments. The prototypical model for a movement representation in cognitive perspective was a hierarchical structure (Schmidt & Lee, 1999). The internal representations are believed to contain detailed instructions to regulate movement behavior.

An important idea in the cognitive perspective for explaining perception and action was originally proposed by Poulton (1957, 1965). He argued that two types of predictive information were necessary for the successful performance of interceptive actions, such as catching or hitting. In the first type, a clear view of the object (a ball) allowed receptor anticipation information to be obtained on the time of arrival of the ball at the catching hand. Successful interceptive actions are dependent on a series of complex differentiations involving brief observations of velocity and distance cues from ball flight which are related to past memories of similar events (Bruce et al., 1996; Gordon, 1989; Savelsbergh, 1990). Extensive experience in such a situation allows observers to develop an internal algorithm to compute the value of each variable when extrinsically timing an action. For these computations, observers need knowledge about the size of an approaching object before perceived information about velocity and

distance can be scaled into the algorithm for computing time-to-contact. The observer computes time-to-contact by dividing the object's momentary distance from the eye by its current velocity (Tresilian, 1991). Knowledge about object size is acquired through specific experience in a particular performance setting and is symbolically represented in the memory component of the information processing system. Thus, the more relevant interceptive information stored in memory, the more accurate the anticipatory timing behavior.

Consequently, Savelsbergh et al. (1993) noted that for catching behavior the main questions during the past three decades have reflected concerns about the amount of information necessary to make decisions rather than the nature of that information. This was the rationale behind manipulating the viewing time of a ball. In particular, the extent and the location of viewing time along the flight path of the ball were experimental variables in numerous catching studies (Sharp & Whiting, 1974; Whiting et al. 1970; Whiting & Sharp, 1974). The critical questions revolved around (a) how much information needed to be present in the information processing system during a successful catching performance, and (b) the exact point in time when that information needed to be accessed by the performer's perceptual system.

The second type of predictive information concerned when to initiate the movement, called the perceptual anticipation process. Knowledge of the temporal duration of an interceptive action, such as a bat swing or a reach-to-catch, allows a performer to correctly predict when to initiate the movement. Cognitive theorists argue that extensive practice (initiation and execution) of a movement allows movement to be included in a repertoire of programmed actions in a high-level performance, and the

successful selection of correct movement program is dependent on accurate perception of ball flight characteristics (Franks, Weicker, & Robertson, 1985; Tyldesley & Whiting, 1975).

Furthermore, Abernethy and colleagues (Abernethy, 1981, 1987a, 1987b) pointed out that skill in rapid interceptive actions, such as catching and hitting balls, is based on the ability to detect and interpret perceptual information through a comparison with an internalized memory based on past experiences in similar situations. The cognitive perspective suggests that experienced performers form situational probabilities of events to plan action in advance. In time-constrained environments, the ability to detect and interpret early cues allows the catcher to better prepare the appropriate movements quickly to execute the interceptive action because the signals from later ball flight are redundant and only carry minor information. Additionally, the ability to program basic posture and orientation of movements in addressing the approaching ball is believed to free the attentional mechanisms of the expert player to focus on more sophisticated cues regarding what to do with the ball once it has been intercepted. In catching, successful perceptual-motor action demands conformity to highly constrained spatiotemporal requirements; namely, placing the hand at the right moment at the required spatial location, and closing the fingers at the appropriate moment in time (Anderson, Sully, & Sully, 1974; Savelsbergh, 1990; Savelsbergh & Whiting, 1992).

A failure to meet these requirements gives rise to two kinds of error: temporal and spatial. Thus, the main question from these studies is how long the visual information takes to be processed. Furthermore, what kinds of visual information are used for the control of ongoing movement during catching is important. These questions are essential

because answers provide fundamental information for understanding functional capacity as well as the limit and the role of visual information in producing skilled anticipatory movements.

Cognitive Perspective: Historical Contribution

An early attempt to address the question about timing the arrival of a ball was conducted by Hubbard and Seng (1954). They employed an innovative strategy to examine whether professional baseball batters needed to watch the ball for the entire flight to successfully strike it. To test the assumption that batting excellence is a combination of visual ability and extensive experience in sport, they filmed the batting performance of 29 professional batters during practice. Through careful positioning of the camera and the use of a large mirror they were able to record the entire duration of 70 pitches from release of the ball to bat contact. The results suggested that skilled batters could only track the ball up to 2.4-4.5 m from the plate. No further head or eye movements were recorded after this point. Furthermore, the batters seemed to reduce the scope of the motor control problem by coupling the step before the striking with the release of the ball from the pitcher's hand. Thus, step duration was constrained by pitch velocity; faster pitches induced shorter steps and slower balls warranted longer steps. This strategy allowed the duration of the swing to be kept constant and independent of ball speed.

The lack of late eye and head movement results were interpreted as an indication that extensive practice allowed performers to develop an internal representation of the event by using early cues from the action of the pitcher and the flight of the ball, respectively. Later stages of ball flight were redundant due to the knowledge of the

batters of the characteristics of various types of pitches. Bahill and LaRitz (1984) provided support for the early findings of Hubbard and Seng (1954) by demonstrating that baseball pitches often reach a level of velocity that exceeds the tracking capabilities of the eye movement system. However, many baseball batters are capable of exquisite timing.

Although the study by Hubbard and Seng (1954) has been described as ‘classical’ (Bootsma & Peper, 1992), they did not attempt to provide any theoretical explanation for their findings. The study was non-theoretical in the sense that the authors were driven by a practical problem: Do skilled athletes keep their eyes on the ball all the time during interceptive actions? There was little attempt to integrate the findings into a theoretical framework on the nature of a perception-action relationship. Clearly, to achieve the objective of providing a theoretical explanation of motor control during interceptive actions, a comprehensive and systematic approach is needed.

Such a systematic approach was achieved by Whiting and his colleagues (Whiting, 1968, 1969, 1970; Whiting, Gill, & Stephenson, 1970). Their approach was mainly influenced by the perceptual moment hypothesis (Shallice, 1964; Stroud, 1955). Whiting and his colleagues viewed the performer as a discrete processor of ambiguous cues requiring cognitive confirmation and interpretation by relating these signals to an internal representation of performance.

According to Savelsbergh et al. (1992), a major issue raised by extrapolating theoretical ideas on the perceptual moment hypothesis to the study of ball skills concerned the minimum amount of information needed to support successful interceptive actions. Initial theoretical work in experimental psychology identified periods around 80

ms to 200 ms as appropriate for information processing purposes (Shallice, 1964; Stroud, 1955). However, whether the values of 80 ms to 200 ms would extrapolate to real sport contexts is debatable. Occlusion technique studies were designed to ask a question about the time sequences (Williams et al., 1999). The technique allowed experimenters to light up a ball (in ms) as it traveled toward the catcher for short periods of time in a totally dark room. The earliest study using this research technique (Whiting, 1968) provided support for the seminal findings of Hubbard and Seng that accurate interceptive actions did not depend on the performer tracking the ball with the foveae of the eyes for the whole duration of flight. Later studies attempted to verify the existence of critical time periods for processing ball flight information and particularly when these critical time periods were most informative (Sharp & Whiting, 1974; Whiting & Sharp, 1974; Whiting et al., 1970; Whiting et al., 1973).

Although there was a large amount of individual variation in catching performance, Sharp and Whiting (1974) provided evidence for a critical viewing period of 80 ms to support successful one-handed catching. Viewing periods of less than 80 ms resulted in poorer catching performance. However, the occlusion technique placed an inordinate emphasis on the less representative processes participants used, in conjunction with past memories, to perceptually construct parts of occluded ball flight (Davids et al., 1994; Williams et al., 1992). A significant constraint on the behavior of the participants of Sharp and Whiting (1974) was the total time for which they could use the processes of receptor and perceptual anticipation. There was a clear preference, where feasible, for receptor anticipation strategies. Savelsbergh et al. (1992) pointed out that it is hard to separate the influences of the viewing periods and occlusion periods to attribute to one

effect on catching behavior. More importantly, the results from several studies showed that the longer the ball was foveally tracked, the more successful were the catching performances (Sharp & Whiting 1974; Whiting et al. 1970; Whiting & Sharp 1974). Most of the studies found that the greatest number of catches were made under fully lighted conditions where no flight cues were occluded. This finding is contradictory to the assumption postulated by Whiting et al. (1970). Even skilled catchers caught more balls under the full light condition. According to Williams et al. (1999), a question arises from this finding: If there is a minimal viewing time to process visual information from an external event within 80 –200 ms, why does the full light condition show superior performance compared to the occlusion condition?

Further studies examined skill level differences and allowed participants to manipulate whether they watched the ball or the target at any given time (Whiting, 1970). Whiting attempted to resolve whether experienced catchers used different sources of visual information than inexperienced performers and to determine when during flight catchers need to process visual information cues for successful response. The length of time, for which the ball or target was illuminated, was assumed to be the visual processing needs. Results revealed that participants preferred the illuminated ball rather than the illuminated target. Also, a significant tendency to process visual cues earlier in ball flight with increasing trials was identified. Furthermore, when the ball was illuminated for shorter periods, competent performance was based on fewer flight cues with practice. The cognitive perspective explanation for these findings suggested that participants learned to recognize the sequential dependencies of flight by invoking the inferential processes involved in perception and memory. These results were interpreted

as supporting the important role attributed earlier to the cognitive processes of perception and memory in time-stressed and visually-degraded environments.

However, Whiting (1970) neglected to specify a minimal viewing period for performance. Also, he admitted that the relatively short flight path placed too great an emphasis on an individual's reaction and movement times, which may have accounted for much of the variance in the data. Furthermore, a failure to prevent the more experienced group from using a familiar strategy with the oncoming ball, as they were accustomed to in "real life" games, resulted in them effectively extending the viewing period.

Other attempts to validate the length of critical time periods for viewing a ball in one-handed catching followed. For example, a longer flight path (6 m), more elaborate skill groupings based on expertise in cricket and table tennis, and the use of a ball projection machine to standardize flight patterns (Sharp & Whiting, 1974; Whiting, Alderson & Sanderson, 1973; Whiting & Sharp, 1974) were critically evaluated to prevent the confoundings. Critical viewing periods of 100, 150, 225, and 300 ms were used to investigate the prevalent cognitive notion that the human performer was a discrete sampler of the environment. Further support was provided for the importance of watching the ball for as long as possible, although skill differences were not forthcoming, which may have been indicative of the lack of ecological validity inherent in the occlusion technique.

Moreover, a reduction in viewing time of 75 ms often led to a significant decrease in catching success. Performance was best when the critical viewing period occurred in the middle region of flight. This specific finding, when the ball was not viewed for a

significant portion of the middle section of flight, identified the burden on the perceptual processes that led to a performance decrement (Sharp & Whiting, 1974; Whiting & Sharp, 1974). A viewing period of 80 ms represented an approximate value for a discrete "perceptual moment" during catching and when this occurred early or late in flight, performance became problematic. An information processing explanation was offered for this effect in that the time for which the ball is both seen and not seen may be critical determinants of successful catching performance (Sharp, et al., 1974). Furthermore, the reliance on simple outcome measures such as the number of balls caught prevented a more detailed analysis of the effects of visual degradation of the environment on movement quality (Bootsma et al., 1989).

From an ecological perspective, because of the constraints imposed by the information processing approach, the occlusion studies failed to extend understanding much beyond a general statement regarding when to watch the ball during catching performances. A significant problem may have been the tendency to conceptualize sport actions in the same way that many contemporary cognitive psychologists viewed movements, as composed of simple modular components that could be isolated from the environment in which they were performed. These limitations are discussed in more detail in the next section.

Limitations of the Cognitive Perspective Approach

First, a considerable number of artificial movement patterns in laboratory settings for catching studies were used in the occlusion paradigm (Bootsma, 1989; Bootsma & Oudejans, 1993; Tresilian, 1994, 1995). In fact, the lack of ecological validity in the studies in which balls were always projected and caught in the dark led many participants

to complain of suddenly seeing the ball appear out of darkness (Nessler, 1973; Sharp & Whiting, 1974). This issue of artificially-induced adaptation in movement organization during one-handed catching, between the occluded laboratory condition and more realistic settings, sometimes received explicit acknowledgement. For example, Whiting, Gill, and Stephenson (1970) noted such a difference in their study. Under a restricted light condition, participants moved their hands forward to the catching point and caught with snatching motion whereas under the full lights condition there was a tendency to move with the ball and the ball was caught similar to a smooth catch of a game situation. Apparently, individual variations in adapting to the dysfunctional technique confounded the work. The severity of time constraints even led to a debatable intermediate scoring criterion for successfully locating the ball with the hand in flight in an attempt to increase the sensitivity of the measurement system. Additionally, there was no detailed analysis of the quality of the spatial and temporal characteristics of catching performance.

Secondly, the confounding effect of viewing time and concomitant occluded periods of flight were both criticized (Sharp & Whiting, 1974; Whiting & Sharp, 1974). It was impossible to tell whether a reduction in the viewing periods or an increase in the concomitant occluded period was predominantly responsible for successful catching performance. Indeed, the occlusion approach appeared to change the basis of the task from the more typical receptor anticipation process to perceptual anticipation process.

These issues call into question many of the conceptions of the cognitive perspective in the study of visual perception in sport. Neisser (1976) argued that artificially created experimental paradigms in the laboratory generated artificial behaviors in participants. Clearly, previous research based on the cognitive perspective to specify

precise details about the nature of the perceptual processes which underlie successful performance in complex tasks such as ball skills was overly optimistic. The integration of desirable elements of laboratory control with more realistic task settings appears to be the best way in which sport science research can contribute to the understanding of the relation between perception and movement organization (Davids, et al., 1994, 2001). Further, Schmidt and Lee (1999) argued that the resulting theories were studied with simplistic tasks that seemed to be demanded by the process-oriented approach. They implied that the cognitive approach should be replaced in favor of the study of perception and action for a more ecological type of analysis.

Therefore, much of the catching behavior in the light occluded laboratory may not have been representative of real life events, and specialized techniques, stressing reaction time and snatching movements, may have been implemented by many of the more resourceful participants to adapt to the demands of the specific circumstances. In an attempt to specify the extent of perceptual moments precisely, a significant amount of experimental artificiality was undoubtedly induced. The resulting conclusions based on the notion of total information processing time, the covariation of the viewing and occluded periods (Sharp and Whiting, 1974), may be useful in explaining participant behavior in the laboratory but such a conclusion contributes little to an understanding of the mechanisms underlying real-life catching skills.

Ecological Perspective: Perception and Action

With the recent interest in ecological psychology, arising from the influential work of Gibson (1966, 1979), there has been a growing interest in the study of natural skills and a deliberate focus on coincidence timing as an avenue to understanding the

normal functional coupling and interaction between perception and action. Gibson (1966, 1979) argued that visual perception is not a retinal image itself, which is passively sensed through inference and recourse to memory. Visual perception involves an ambient optic array that animals use to actively pick up the information needed to guide their actions.

Basic Assumptions

The ecological perspective explains that the visual information needed to guide the observer's actions is available in the structure of the ambient light present at a point of observation. This perspective is based on the premise that visual information may be picked up from sensory input in the optic array without cognitive processes, because of the close fit that has evolved between the perceiver and the environment (Gibson, 1979). Further, Turvey (1986, 1992) argued that the relationship between an animal and its environment is reciprocal and the control mechanism for the actions of a species is neither solely within the organism nor in the environment but highly interactive and coupled. An ecological approach describes a living system and environment as constantly engaged in energy transactions (Williams et al., 1992). In sport, a mutually constraining relationship exists between an athlete and the performance environment. The athlete relies on the information in the environment to support the coordination of actions in relation to important events, objects, and surfaces (Gibson, 1979). Moreover, actions then change the structure of the energy distributions within the environment in meaningful ways.

Flow Fields and Force Fields

Gibson (1979) argued that an animal becomes specifically attuned to the information available in perceptual flow fields. That is, an animal becomes attuned to a

single or few key invariant parameters continuously available in the structured energy gradient of optical flow fields. Changes in the values of these perceptual invariants become tightly coupled to the intrinsic dynamics of a complex biological system to act as control parameters. When the changes of control parameters reach a critical level, they specify changes afforded to the state of the biomechanical system as the result of force field changes. Force field refers to the neuromuscular system's ability to reconfigure energy informational couplings between flow field and force field parameters. In this way, the highly complex interactions between an animal and its environment can be modified and regulated. Appropriate flow field and force field (perception and action) couplings emerge as an animal discovers the optimal way to influence meaningful changes to its environment (Williams et al., 1999).

Energy in the form of light reflected from surfaces and environmental objects is available for pick-up by all animals through the process of perception. All animals inhabit a visual mosaic known as the optic flow field. Given that light energy travels in rectilinear pathways as it is repeatedly reflected from the surface and objects in the environment, makes it a powerful source of information. The way light reflects off surfaces and textured elements in the environment allows a geometric specification of its layout. As we move, light energy flows in a regular way providing an organism, equipped with the appropriate sensors, to detect change in light energy with an ambient flow field of optic information. Optic flow is not ambiguous. Indeed, optic flow contains variants and invariants because the environment is lawfully structured. Due to the dynamic nature of the interactions of an animal with its environment, the dense structure acts as a flow field. Consequently, the detailed structure of optic flow fields in sports is readily

available to the eye of performers in motion. The changes in the optic flow field brought about through motion provide the transformations which allow the lawful invariants, forming a high-order description of the environment, to be perceived by an animal (Gibson, 1979).

From a sport perspective (e.g., ball catching), the ecological emphasis on the structured nature of energy fields flowing in the environment suggests that veridical information is continuously available for pick-up (Turvey, 1992). These arguments propose that the world is already full of meaning which does not have to be inferred from an internal representation. Fitch and Turvey (1978) rejected the reliance of cognitive theories of perception on animal-neutral descriptions of information by traditional physics (e.g., light reflected from an object such as a ball is measured in metrical units related to its intensity or wavelength). An ecological account of perception emphasizes that information is perceived in animal-relevant terms. Therefore, this perspective argues that perception-action coupling involves the kinematic coupling over space and time between the human biomechanical system and information from the environment. Skilled behavior can be lawfully described by the coupling of perceptual information to actions or system states. In other words, information from the environment is used by the performer to regulate motor activity on-line. Figure 1 shows a schematic perception-action coupling process as a function of force and optic flow fields.

Concerning the perception and action coupling process, the ecological perspective theorists believe that the more static visual displays often used in cognitive research do not allow the perceptual systems to function as they were designed to in real environment settings. They argue that the structure of the optic array and the optic flow field

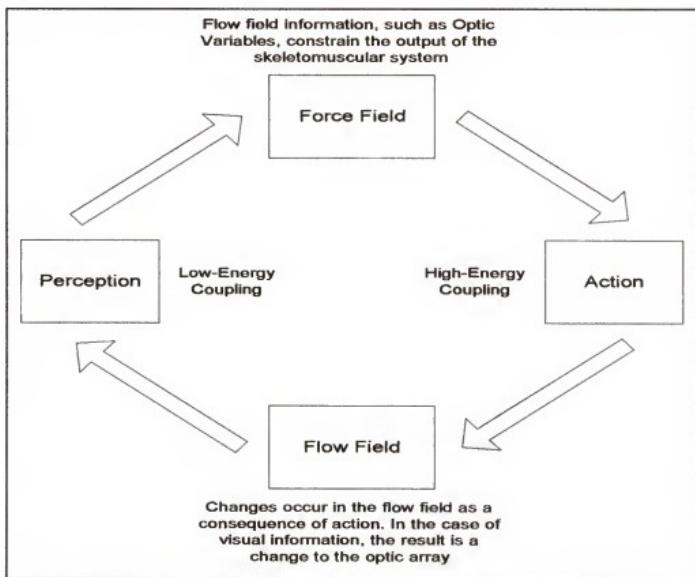


Figure 1 Perception-action coupling from force and flow fields.

generated by relative motion between the observer and objects within the environment, lawfully specifies the layout of the surrounding surfaces, the observer's motion relative to those surfaces, and the nature of events occurring within the surroundings (Williams, et al., 1999). This spatiotemporal information within the optic flow field in turn lawfully specifies the action and response (Turvey & Carello, 1986). Thus, ecological perspective theorists view the perceptual information available at a point of observation not as static and impoverished but rather as dynamic, rich, and complete.

Environmentally generated optic flow fields and actor-generated dynamic force fields are viewed as causally linked in perception and action cycles (Kugler & Turvey, 1986; Turvey, 1992). An example of a causal link involves the laws of physics. This causal link underlies and describes all types of motion, gives rise to laws of ecological optics for the perception of motion and these in turn give rise to laws of control specifying the observer and actor's response (Warren, 1988, 1990). From such a perspective, invoking internal representations is exchanged for a search for the lawful basis of perception and action systems. Clearly, Gibson's view provides a challenge for the results and findings of the cognitive perspective.

Research from the ecological perspective focuses on the search for (a) invariants within the optic flow field (and the flow fields of other modalities) capable of specifying the essential information to guide action, (b) spatiotemporal invariants to specify direction, speed, and force (in actor-scaled units), and (c) identifying objects and events and the affordances they present for action. According to Turvey (1992), this is in keeping with a fundamental philosophical and analytical tenet of ecological realism and observer-environment synergy rather than dualism.

The potential for looming or optical dilation to signal information about the time-to-contact of approaching objects or surfaces was first highlighted by Purdy (1958) and later Carel (1961) and Schiff (1965). In 1975, Lee and Lishman demonstrated that the optic flow field information constrained balancing behavior in children and adults. With a fixed floor and moveable walls, considerable postural sway was induced in participants by moving the walls slowly forward and backward. Furthermore, the direction of sway was dependent on the direction the walls were moved. Participants compensated

appropriately for what they perceived as forward or backward motion signified by the changes in visual flow field. This example of a simple coupling of the force field by manipulation to the optic flow field led Lee and Aronson (1974) to characterize their participants as ‘visual puppets’ whose behavior was driven by the visual information (Davids et al., 1994).

Tau Hypothesis

Lee and his colleagues (Lee, 1980; Lee & Aronson, 1974; Lee et al., 1982, 1983) argued that regularities in the ambient optic structure may serve as a powerful source of information for coordinating and controlling the actions of sport performers. The best developed optic invariants to which performers may become attuned with experience is ‘tau’ (Lee, 1976). Tau is an optic variable which is used to specify the time-to-contact of impending collision with an object or surface in the environment. Specifically, tau is defined as the inverse of the relative rate of dilation of an approaching object’s image on the retinal plane of the observer (Lee, 1976). An example of the use of tau in sport occurs when soccer goalkeepers become attuned to the invariant information generated by the rate at which the optical image of an approaching ball expands on the surface of the retina. The elegance of such an explanation lies in the reduction of a degree of freedom for the action system to control. When tau reaches a critical value known as tau margin, goalkeepers can predict the moment to initiate a movement to parry the shot. That is, tau permits goalkeepers to maintain relative movement invariance in parrying an approaching soccer ball. Goalkeepers do not need to compute the speed-distance ratio and initiate a stored motor program to carry out this task. Also, the regularities of past images of a moving ball need not be represented within the performer for comparison with static

images of an actual ball in flight (Williams et al., 1992). The invariants of ball flight are continuously available and only need to be picked up by a purpose-built visual system specifically adapted for such a task (Runeson, 1977). The logic of the ecological perspective on the perception-action relationship has been clearly summarized by Bootsma and Peper (1992):

In terms of the evolutionary pressures that have acted upon almost all visually equipped species, it makes sense that an observer confronted with an unknown approaching object does not have to rely on estimates of distance and velocity based on ambiguous cues (or worse, have to wait until binocular information becomes available), but is able to perceive the time remaining until collision, and hence act accordingly.(p. 289)

The original mathematical formalism demonstrating proof that timing behavior may be controlled by the optic variable tau has recently been extended to the provision of time-to-contact information between objects or surfaces other than at the point of observation (Bootsma & Oudejans, 1993). The availability of tau for the approach of an object to an environmental location other than at the point of observation is a useful advance for sport and exercise scientists. Tau shows how timing information regarding the relationship between two surfaces of interest in the environment can be perceived. For example, when a ball is approaching the surface of a cricket bat, tau may be used for timing the onset of wrist flexors to deflect the ball away from a fielder by specifying the rate of constriction of the optical gap between the two surfaces. Because this optic information is available continuously from the light energy reflected from objects and surfaces in the environment, skillful athletes are capable of making very precise ongoing modifications to timing behavior. This geometrical description may explain the performance decrements typically found when visual access to the final segment of ball

flight during one-handed catching is denied (Davids & Stratford, 1989; Fischman & Schneider, 1985; Smyth & Marriott, 1982).

For example, Davids and Stratford (1989) occluded the gap between the ball and catching surface for the last 150 ms of the flight path. Participants had significant problems in orienting the palm of the hand in the line of flight of the ball and found the grasp action particularly difficult to time. Perhaps continuous visual information from the spatiotemporal details of the ball's flight path was needed for fine-tuning of the ordered state of the degrees of freedom of the catching limb (Jordan & Rosenbaum, 1989; Turvey, 1990; Warren 1984, 1988; Warren & Whang, 1987). The ecological perspective approach to perception and action views the human biokinematic system as self-reading and self-writing (Kugler, 1986). There is no need to invoke instructional devices for prescribing the pattern of contractions in specific muscles in concert with feedback and feedforward information. The system is execution driven to maximize flexibility in a way that representational devices of movement control cannot match. The issue of movement variability, highly problematic in artifactual accounts of motor control, becomes an asset to be exploited (Kelso, 1992; Kelso & Ding, 1993; Newell & Corcos, 1993; Wing, 1992). This form of functional variability allows the performer to initiate a virtual action to exploit sensitive dependence on initial conditions of flow field energy (Kugler, 1986; Turvey, 1977). For example, Bootsma and colleagues (Bootsma et al., 1991; Bootsma & van Wieringen, 1988, 1990) have demonstrated how compensatory variability is used by top-class table tennis players in modifying a drive to exploit ongoing changes in conditions such as swerve or spin on the ball.

As energy enters the system (in this case, visual information specifying the relative rate of dilation of the retinal image of the ball), critical levels are reached. The temporary symmetry to which the biomechanical system has been attracted (perhaps taking on the topological form of a forehand drive) becomes unstable. The system then uses the inherent variability in the attractor state to achieve a functional modification to the original action. That is, information from the environment allows the system to track onto the appropriate attractor orbit for a successful forehand drive under different conditions. Thus, tau is attractive because it allows visual support for a whole range of coincidence-timing skills to be provided without the need for cognitive mediation and hence without the imposition of a large computational load on the observer. In the following section, the early behavior studies will be discussed.

Ecological Perspectives: Early Supportive Results

Over the past three decades, the ecological perspective has dominated in visual perception and action research, providing solid results for supporting the theory with various types of tasks and participants. Studies of human infants (Ball & Tronick, 1971; Bower, Broughton, & Moore, 1970; Dunkeld & Bower, 1980; Nanez, 1987; Yonas et al., 1977) along with studies of young chickens (Schiff, 1965; Tronick, 1967), monkeys (Schiff Caviness, & Gibson, 1962), and crabs and frogs (Schiff, 1965) have systematically revealed the presence of the avoidance response to optical expansion (called looming effect) within two dimensional displays. These responses, which occur without any real change in observer-object distance or relative velocity, have been shown to be present essentially from birth, and consequently appear to be hardwired in to the visual system. These avoidance responses were only evoked by stimulus looming but

were present regardless of object shape, magnification rate, and the animal's degree of learning of the association between collision and pain responses (Schiff, 1965). Moreover, cortical cells have been located in human visual pathway which are maximally stimulated by looming optical displays (Regan & Beverley, 1978).

Initial studies revealed that humans and animals are sensitive to looming and such optical information is also apparently significant. Schiff (1965) noted that rapid rates of expansion were associated with rapid avoidance response and that the initiation of avoidance behaviors appeared tightly coupled to the time remaining before collision. Later, the plummeting gannet studies reported by Lee and Raddish (1981) and the housefly studies by Wagner (1982) showed the initiation of the landing leg action when the projected time-to-contact with the surface reaches a critical value. The gearing of the animal's action to time-to-contact theoretically allows precise coincidence timing to be achieved across a range of approach velocities without the necessity for the animal to adjust the duration of its wing folding or leg extending movements.

Sport Context Research: Tau Evidence

Empirical support for tau has been found in research on the visual regulation of action in various types of sport. Consistent movement initiation times have been demonstrated across variation in observer-object (or observer-surface) approach velocity for the swing of baseball batters (Hubbard & Seng, 1954), table tennis players (Bootsma & van Wieringen, 1988, 1990; Tyldseley & Whiting, 1975), field hockey players (Franks, Weiker, & Robertson, 1985).

Dietz and Noth (1978) required participants to fall forward, hands first, from a vertical standing position through a range of between 50° and 80° to a padded platform.

They observed that the onset of electromyographic (EMG) activity in the triceps brachii always occurred at a specific time-to-contact value. Moreover, this coupling of movement initiation of time-to-contact disappeared when vision was eliminated.

The modulation of flight time in gait in the response to actual time-to-contact with a specific target surface is a second major source of support for the primacy of time-to-contact information. For example, long jump coaches instruct athletes to set a stereotyped approach run to ensure hitting the take-off board correctly. Indeed, jumpers often practice the run-up alone without jumping. Perhaps the jumpers are building a precise motor program which can be relied upon for producing a consistent stride pattern in the run-up phase. However, data with elite jumpers have shown that about five strides before the take-off board a remarkably high level of irregularity (i.e., higher variability) in footfall placement typically occurs (Hay, 1988; Hay & Koh, 1988; Lee et al., 1982). This movement variability contrasts significantly with the earlier segment of the run-up, which can show a variation in average foot placement accuracy of less than 8 cm within each stride (Lee et al., 1982). The ability of elite jumpers to replicate their early stride pattern before they approach the take-off board is highly consistent given a typical approach run of 35 m, but the final five strides on the take-off stage is not.

Lee et al. (1982) proposed an ecological framework for understanding the timing behavior of expert long jumpers. The authors argued that international-level jumpers subconsciously used light energy reflected from the take-off board (flow field information) to modulate their stride pattern (force field activity) to strike the board successfully. The higher variability of the pattern in the last few strides is believed to be evidence of a switch to a strategy of visual regulation on the part of the athlete (Lee et al.,

1982; Turvey, 1990). The use of light information reflected from the take-off board permits the athlete to correct the earlier error that accumulated in the run-up phase.

Cognitive explanations for run-up performances have emphasized the role of sensory feedback loops, which parameterize the general motor program through a continual process of comparison with a central representation of the activity (Schmidt & Lee, 1999). Lee et al. (1982) argued that it may be a critical change in the optic flow (in this instance, the relative rate of dilation of the image of the take-off board on the retinal surface) which results in the movement system destabilizing into a more functional attractor state.

The ecological psychology model appears more parsimonious than the cognitive perspective because there is a significant reduction in the number of degrees of freedom to be controlled by the athlete. When the optic variable tau reaches a critical level, a modification to the order parameter, (i.e., the vertical impulse of the footfall) is specified for the performer. Consequently, the estimated variance in footfall position may be subconsciously increased by as much as 53% in the final phase before the system achieves a symmetrical state at the take-off board. Also, a funnel shape in the reduction of the estimated variance in footfall placement occurred in the last five strides. A similar distribution of the estimate of variance was found by Bootsma in studying the forehand drive of expert table tennis players.(Bootsma & van Wieringen, 1990; Bootsma et al., 1991).

Sidaway et al.(1989) demonstrated that preparatory muscle activation prior to impact landing from different vertical heights is triggered at a specific tau margin. Laurent, Dinh Phung, and Ripoll (1989) demonstrated that participants used the retinal

expansion pattern of the obstacle for the regulation of gait in horses jumping obstacles. These results could be interpreted as substantial evidence that human and other animals are sensitive to information about the time remaining to contact with approaching objects or surfaces. Across changes in the approach velocity of objects or surfaces, the initiation of interceptive movements seem to be consistently geared to time-to-contact rather than to other potential visual control variables. Thus, these findings provide evidence in support of the explanatory power of an ecological perspective explanation of control of timing in a variety of skills.

Although the logic of Lee and Young's argument is convincing and the evidence is compelling, the timing of movement sequences with the use of the optical variable tau (Lee & Reddish, 1981; Lee et al., 1983) is not sufficient to prove that the relative rate of dilation is responsible for such timing. The expansion pattern has never been experimentally manipulated (Savelsbergh, Whiting, & Bootsma, 1991, 1993). Additionally, a second issue is that some tasks, including computer simulation (Todd, 1981), discrimination (Schiff & Detweiler, 1979), and simple button-presses were not sufficient to evaluate the proposed continuous coupling of perception and action.

For example, Schiff and Detweiler (1979) required participants to indicate the time to contact estimate. Several background manipulations were introduced to provide enhanced distance or distance change information. None of the background manipulations used were found to influence the accuracy of judgments in relation to the two dimensional terrain. They concluded that observers can and do use two dimensional time-to-contact information to estimate impact time. However, it is important to note that the task was that of a perceptual judgment alone because participants were not required to

carry out actions more complex than pressing a button. In addition, because of the early curtailment of the projection, no information on the last 2 sec. of the moving object's trajectory was available.

Bootsma (1989) questioned the validity for visual timing on the basis of button pressing. In his studies, participants were required to (a) strike a ball with a table tennis paddle, as a squash ball dropped along a fixed path, (b) release an artificial arm to hit a similar ball, and (c) to press a button when the ball reached the point of contact. All three actions were carried out under similar optic flow patterns. The results indicated that the variability of the moment of initiation was considerably smaller under the artificial arm condition than under the button pressing condition. The more the required action was separated from a natural perception-action coupling, the less precise the timing response.

Bootsma (1989) argued that there was no visual information of the expanding optical image from an approaching ball in the last 2 s. Such information might be important in those tasks such as catching a ball in which participants have to carry out an action to intercept an approaching ball. This concern was earlier confirmed in Alderson and Sully's (1974) analysis of ball catching, in which the grasp phase of the catching action occurred about 40 ms prior to contact.

Manipulation of Optical Image Size

In a one-handed catching task, if the theory of perception-action coupling is valid, then some predictable changes such as the kinematics of the grasp phase should be revealed. One-handed catching is a highly intricate skill since the optimal area for receiving the ball at the hand that area just above the palm and at the base of the knuckles is very small (Alderson et al., 1974). Once the hand is spatially oriented in the correct

line of flight, a major problem is the timing of the grasping action. Closing the fingers too early results in the ball striking the knuckles or too late causes the ball bouncing out of the palm. The margin of error for catching a ball traveling at a speed of 10 m/s has been calculated at around ± 15 ms (Alderson et al., 1974). Because of these severe time constraints, anticipatory muscle responses must be implemented so that the maximum aperture of the catching hand occurs before the ball contacts the palm, and the finger joints have to be prepared for stabilization against impact.

Lacquiniti and Maioli (1989) pointed out that the visual information that is presumably needed for triggering anticipatory responses with appropriate timing relies on continuous sensory inputs providing instantaneous estimates of the time-to-contact. An important question is: What are the sensory inputs that skilled catchers use for predicting when to initiate the onset of the grasp? Logically, if tau is used to initiate an action, then perturbing the pick-up of tau should be manifested in changes to the kinematics of interceptive timing behavior. Clearly, two important tasks to test this tau assumption are evident: (a) the direct manipulation of the visual information used in controlling actions, and (b) the kinematic profiling of adaptations to the patterning of the grasp action as a function of perturbations to the optic array.

Lacquiniti and Maioli (1989) attempted to achieve both of these goals by analyzing the temporal constraints on a form of one-handed catching using EMG and kinematic measurements as well as outcome measures. Participants caught a ball of uniform weight (0.4 kg) dropped from different heights (0.4, 0.8, 1.2 m) with and without vision. In the vision condition, EMG preparatory activity in which the flexors and extensors of the catcher's arm were fully activated at the final 100 ms before hand-ball

contact. The analysis revealed that mean EMG amplitude was significantly smaller in the no vision condition compared with the full vision condition for the final 50 ms before impact for six muscles of the arm. Wrist and elbow kinematics also varied between the conditions. Without vision, changes to elbow and wrist joint angles were most pronounced 50-100 ms after impact. Peak angular displacement of the elbow and peak extension velocity were significantly larger at this time than with vision (1.3 times larger in the case of the first kinematic variable). In vision, the movement had greater equilibrium and was more stable and less expansive. Without vision, the variability in the sum of wrist and elbow angular velocities was 1.23 times greater than in the control conditions.

The results indicated that access to ongoing visual information allows catchers to use more efficient preparatory movements than under no vision condition. However, although visual information about the ball was suppressed in one condition of this experiment, participants may have been able to rely on other sources of information for timing the grasping action. For example, they could have used prior knowledge of ball flight and/or auditory information when the ball was released for timing the stabilization of the wrist and fingers against ball impact. Additional trials were conducted in which these alternative sources of information were suppressed. In these conditions, an absence of anticipatory muscle responses, much smaller short latency bursts immediately after impact, and far greater and more prolonged variability in elbow and wrist angular displacement (i.e., 1.81 times more variable than in control conditions) were observed. In these cases, some catching errors were evident because of the failure to time the grasp phase correctly. The data from these comparisons can be interpreted as support for the

role of time-to-contact information within the final 100 ms before hand ball impact in successful execution of the grasp.

These precise behavioral findings are predicted from the nonlinear, looming effect in the mathematical modeling of time-to-contact. When vision was not available, time-to-contact information could not help the performer to prepare anticipatory muscle responses and there was a shift in emphasis to a more reactive mode of control in which medium and long latency reflexes (active 40-200 ms after ball-hand contact) stabilized the wrist and fingers after impact. In fact, Lacquinti and Maioli (1989) were cautious about implicating the optic variable time-to-contact in timing the grasp phase during the vision conditions because the dropped ball was accelerating and was not in the direct line of sight of the inexperienced catchers.

Savelsbergh et al. (1992) examined the role of time-to-contact in a behavioral study of four relatively experienced participants catching balls projected directly towards them from a distance of 6 m. High-speed film analysis (200 Hz) and EMG data were used to examine the relationship between predictive visual information and the onset of muscle activation for the initiation of the grasp at three different ball velocities (11.9, 13.9 and 16.2 m/s). The logic was that if time-to-contact was being used to time the grasp, the activation of anticipatory muscle responses would be independent of ball velocity. Tau margin data for each participant was calculated during one-handed catching, operationalized as the time interval between the hand and the ball at the time of the initiation of finger closing in the grasp phase. Savelsbergh et al. found that tau margins for the onset of the closing time for the fingers at different ball velocities were not statistically different. This finding suggested that EMG activity in the wrist flexors and

extensors was initiated at a constant time before ball-hand contact, rather than at a constant distance or time after ball projection. However, neither power nor effect-size data were reported in this study, despite the possibility that the lack of statistically significant differences could have been a function of the small sample.

Furthermore, although these findings support the work of Lacquiniti and Maioli (1989a, 1989b) on the role of visual information in timing the grasp, no attempt was made to provide stronger support for time-to-contact by implementing an alter-tau and alter-action strategy. Savelsbergh, Whiting, and Bootsma (1991) made an important contribution in this respect in an experiment with a pendulum-based interceptive task purporting to simulate the timing requirements of one-handed catching. Savelsbergh et al. (1991) analyzed several key kinematic variables of the grasp phase while experimentally manipulating the optic flow field. They predicted that the relative retinal expansion velocity of different size of balls attached to a hinged pendulum and approaching the observer at a constant velocity, would be the same regardless of the physical size dimension. According to the original equations, during the approach of a ball towards the observer at constant velocity, at an instantaneous value of tau, the rate of retinal dilation provided by a small ball would be the same as the rate of retinal dilation of a large ball. The question was what would happen to the parameters of the grasp if the rate of retinal expansion of an approaching ball was experimentally perturbed without a participant's awareness?

To answer this question, Savelsbergh et al. (1991) used small (diameter 5.5 cm) and large ball (diameter 7.5 cm) conditions to observe the kinematics of the grasp during one-handed catching. Optical structure, provided by the solid visual angle subtended by

the area of the ball, was manipulated by using a third deflating ball condition. A balloon was inflated to a size of 7.5 cm to cover a small ball (5.5 cm diameter) and it was attached to the pendulum. The approaching balloon was mechanically deflated without the participants' knowledge, so that when it reached the catching hand it was the same diameter as the small ball. Essentially, Savelbergh and colleagues attempted to dissociate the rate of retinal expansion of the image of the oncoming ball from the actual approach velocity to investigate which was the source of visual information that performers relied on to time the grasp. They argued that a deflating ball simulated the approach of a ball traveling at a slower velocity, and the data on the kinematics of the grasp in that condition demonstrated that time-to-contact was consistently overestimated because the retinal expansion velocity of the image of the shrinking balloon did not match its actual velocity.

The time of appearance of maximal closing velocity of the hand was significantly later for the deflating ball condition than for the constant size balls. In addition, the aperture size of the hand responded to the different ball size. The aperture size of the hand was adjusted to the deflating ball, despite participants being unaware that the approaching ball was deflating during its approach. This result strongly suggests that the coupling between the deflating ball and hand aperture size is based on visual information specified directly by the relative optical expansion pattern.

Ecological Perspective: Limitations

Although the ecological perspective for visual perception and action studies has been plentiful, the lack of a comprehensive understanding and agreement within this literature is apparent. Recently, ecological perspective studies have identified a number

of criticisms and limitations of tau and its usefulness as a control parameter for coincident timing.

First, criticisms concern the use of laboratory-based methodologies and level of analysis performance measures for the purpose of examining time-to-contact. The basic methodologies of perceptual experimentation cause concern for the external and ecological validity. These include the use of computer simulation tasks and film stimuli on flat screen displays, which tend to minimize the interactive relationship between the perceptual and action systems.

In particular, the implications of using computer simulations for the study of visual perception and action represents an ongoing controversy in the ecological psychology literature. Michaels and Beek (1995) demonstrated that the invariant energy patterns in the environment that are continuously available as optical sources of information represent affordances for actions. They argued that ecological psychologists have typically failed to apply this principle of Gibsonian theory in designing research studies on perception and action. A major flaw in the design logic of some studies is the belief that perception is about action. Therefore, any ecological study of perception is a study of action and any ecological study of action is a study of perception. Thus, the problem is that when traditional artificial laboratory tasks are used, they often produce outcomes which differ from the findings of behavioral studies of tau using natural tasks such as catching, hitting, and locomotion.

Ecological validity is especially important in examining real-world coincidence timing skills because the use of artificial coincidence timing tasks can substantially underestimate a participant's coincidence timing capabilities (Runeson, 1977; von

Hofsten, 1987). Mean timing errors on contrived laboratory coincidence timing tasks are commonly in the order of 20-50 ms (Abernethy & Crassini, 1989; Blundell, 1984; Haywood, 1980; Payne, 1987) whereas performance on apparently more complex but natural hitting and catching actions occur within time windows of 4-10 ms (Alderson, Sully, & Sully, 1974; Bootsma & van Wieringen, 1990; McLeod et al., 1986; Tyldesley & Whiting, 1975). One reason for these large differences may be due to the impoverished nature of the simulation displays (Bootsma & Oudejans, 1993). Computer monitors present a two-dimensional display which may deemphasize certain sources of information available in the optical structure of the environment. Therefore, this type of information may affect the visual perception and action coupling process.

As Tresilian (1995) emphasized, the variability of responses in coincidence anticipation tasks is five or six times greater than that observed in interceptive timing actions performed under the same stimulus conditions. This finding, particularly with practiced observers and skilled catchers used in many studies of interceptive actions, calls into question the use of coincidence anticipation tasks for testing interceptive timing.

Furthermore, Milner and Goodale (1995) suggested the timing difference involved in tasks between coincidence anticipation tasks and interceptive timing tasks. Also, Tresilian (1994, 1995) highlighted a number of key methodological differences between other laboratory-based studies and natural interceptive actions such as one-handed catching. In laboratory-based studies, there has been a tendency to focus on coincidence anticipation tasks in which participants have to typically predict when a suddenly occluded object/image would arrive at a designated target point. These motion prediction paradigms emphasize perceptual anticipation processes, whereas in the study

of natural interceptive actions such as one-handed catching, the emphasis is on receptor anticipation processes (Poulton, 1957; Williams et al., 1992). For example, in perceptual anticipation tasks, participants are permitted to see only a part of the trajectory of the object image on the computer screen. They are required to perceive part of the approach trajectory of an object image and to predict time of arrival at a target location (Bootsma & Oudejans 1993; Todd, 1981). When a natural task such as ball catching is used, participants are typically able to view the ball until it arrives at their hands. Thus, the typical constraints of motion prediction and natural interceptive tasks suggest that different control mechanisms may be used by actors in the different conditions (Milner & Goodale, 1995).

Secondly, the provision of time-to-contact information through optic variables assumes a constant velocity between a performer and an object or surface of importance (Lee 1976). The estimate of actual time-to-contact, provided by tau (the inverse of the relative rate of retinal expansion) can only be exact when the rate of approach between the observer or actor and the approaching object or surface is constant. Because constant approach velocities are rare in nature, tau-based estimates of time-to-contact may not necessarily contain accuracy in timing. Specifically, when an object is accelerating toward an observer (or vice versa) tau will over-estimate actual time-to-contact whereas under conditions of deceleration tau will underestimate actual time-to-contact (Tresilian, 1991, 1995, 1999; Wann, 1996). Moreover, Lee and Young (1985) argued that the extent of this over- or under-estimation of time-to-contact depends on the duration of the activity. The error is minimal when the actual duration of the time window is relatively small and velocity at contact is high (Lee & Young, 1985).

In studies of the wing-closing behavior of plummeting gannets (Lee & Reddish, 1981), human participants jumping to punch a dropped soccer ball (Lee, Young, Reddish, Lough, & Clayton, 1983), and EMG onset of the catching hand for ball drop of four different ball heights (Lacquanti & Maioli, 1989), the initiations of actions have been shown to be delayed until time-to-contact reaches a critical value known as tau margin. However, Wann (1996) argued that tau was not directly related to the initiation of actions. After reanalyzing the data of well-known references, data from research with plummeting gannets, plunging men, and punching balls in a gravitational free-fall situation, Wann concluded that there is no direct evidence that supports the use of tau in the gravitational free-fall contexts.

Additional issues arise from the studies of Savelbergh and colleagues (1991, 1993). They used a pendulum motion bar with the ball and/or balloon at the end. They reported the constant velocity of 2.4 m/s from the release of ball to the ball contact to hand and assumed that the approaching ball had constant velocity. Based on this assumption, they drew the conclusion that tau was the control parameter to initiate and adjust catching. However, this type of approaching motion did not provide constant approaching velocity information. Wann (1996) showed that the approaching ball had both acceleration and deceleration patterns after reexamination of Savelbergh's et al. (1991, 1993) data. Consequently, the conclusions based on the constant velocity approach assumption were violated (Tresilian, 1994, Wann, 1996).

Despite this limitation of a tau-based explanation, there has been very little work aimed at ascertaining whether tau can be used in accelerative approaches (Lee & Reddish, 1981; Lee, Young, Reddish, Lough & Clayton, 1983). By modeling constant velocity

approaches, the original equations on tau may only have exemplified the limiting cases for the perception of time-to-contact, rather than the most typical requirements for action in dynamic environments (Bootsma & Oudejans, 1993). Therefore, more systematic approaches to acceleration situations should be investigated.

A third criticism focuses on the conflicting results from the monocular versus binocular viewing conditions. If time-to-contact is picked up directly from optical looming, as proposed in Lee's (1976) original tau concept, then this information should be equally accessible to one eye as to two and coincidence-timing performance under monocular, and binocular conditions should be equivalent. However, such equivalence can be expected only if the coincidence-timing task does not involve spatial (directional) uncertainty (McLeod et al., 1986; Savelsbergh & Whiting, 1992; von Hofsten et al., 1992).

McLeod et al. (1986) reasoned that if time-to-contact information was dependent on the pre-existence of distance information then performance on coincidence-timing tasks should be impaired if participants are required to perform the task monocularly rather than binocularly. They compared the monocular-binocular performance of participants on two different coincidence-timing tasks. In the first task, squash balls were dropped vertically toward them, and they were required to strike them at targets using bats of varying widths. In the second task, balls were projected horizontally across the visual fields and they were required to coincide a button-press response with the arrival of the ball at a given spatial location. The first task consisted primarily of temporal uncertainty. Performance, as assessed from the percentage of successful hits, was not significantly different between the monocular and binocular viewing conditions.

A binocular advantage was found on the second task containing both spatial and temporal uncertainty. Abernethy and Crassini (1989) attempted to replicate the McLeod et al. (1986) findings with respect to monocular-binocular equivalence using a coincidence-timing task in which absolutely no spatial uncertainty existed. Motion of between 2.24 m/s (5 mph) and 8.94 m/s (20 mph) was presented to participants down a 4.30 m runway and participants were required to make a thumb-press response to coincide with the arrival of an object at the end of the runway. Consistent with the findings of McLeod et al., equivalent coincidence-timing accuracy (as assessed from absolute error) and consistency (as assessed from variable error) were obtained over monocular and binocular viewing. However, under the monocular viewing condition, participants systematically made more late responses than they did during binocular viewing. Abernethy and Crassini suggested that deprivation of binocular disparity information causes participants to slightly but systematically over-estimate time-to-contact.

More recent findings by von Hofsten et al. (1992) were consistent with the previous studies in that catching performance under a binocular condition was superior to that under a monocular condition. However, these studies did not examine the kinematics of the required movements; only one aspect of visuomotor performance catching (accuracy) was used. This finding is not conclusive for determining the relative importance of monocular versus binocular vision. Another issue concerns the studies of monocular versus binocular vision. If participants with normal vision perform the task under modified viewing conditions after only a small number of practice trials in a monocular vision condition, the question arises whether this limited practice is sufficient to draw conclusions concerning the binocular advantage for catching performance.

Savelsbergh and Whiting (1992) acknowledged this issue and addressed it in experiment in which a total of 900 practice trials under monocular and binocular viewing were administered. After this extended practice, monocular catching was almost as good as in the binocular condition. This result indicates that deprivation of one source of visual information can cause an instant decrease of performance because of a life-time dependency of binocular vision. However, Savelsbergh and Whiting (1992) only analyzed the performance scores of successful or unsuccessful catches. Such a general performance measure is only one aspect of ball catching. Thus, more detailed kinematic analyses are required to confirm and verify the subtle catching differences.

Summary

The major focus of ecological studies on perception-action coupling issues has been on the role of the optic variable tau in timing behavior. Many strong claims have been made for tau in the perception of time-to-contact information during a variety of actions, such as locomotion towards a target and ball catching. Tau seems to be an important control parameter for interceptive timing in sport (Savelsberg et al., 1992).

Studies on the provision of time-to-contact through tau have inspired much confidence in the ecological perspective. This conviction has proposed strong statements on the role of the optical variable tau in perception-action coupling during interceptive actions. Specifically, Savelsbergh and van Emmerik (1992) argued that there is a wealth of evidence that shows that this optical variable is responsible for the timing control of action. However, most recent criticisms have shown that tau is not the only control variable for timing control of action, and that it is limited for various timing actions. Thus,

further research is needed to ascertain whether tau is used as a timing control variable for interceptive timing tasks.

CHAPTER 2 EXPERIMENT I

Timing Control of One-Handed Ball Catching: Gravitational Acceleration

Most studies in catching have focused on information generated by the approaching object. Lee (1976) showed that the inverse of the relative rate of optical expansion of an approaching object directly specifies time-to-contact: tau. Although many studies have provided evidence for the use of this optical variable tau, most of the studies are primarily descriptive in nature, indicating that participants behaved in accordance with a constant time-to-contact strategy (Lee et al., 1983; Savelsbergh et al., 1992; Sidaway et al., 1989). However, because the available visual information sources are not usually manipulated, these results are restricted in providing an answer as to whether tau contributes to visual guidance of interceptive timing actions (Tresilian, 1997, 1999; Wann, 1996). Therefore, a more direct test of tau is necessary; a test that manipulates the optical expansion of the approaching ball while controlling confounding visual variables such as absolute disparity, relative disparity, and perceptual anticipation under a fixed experimental condition.

Successful coordination and control of dynamic interceptive actions demand conformity to highly constrained movement requirements; namely, placing the hand at the right time and at the required spatial location, and closing the fingers at the right moment in time (Savelsbergh & Boostma, 1994; Regan, 1997; Williams et al., 1999). In many types of sports, precise coincidence-timing skills are inherent in highly skilled

performance. Indeed, playing ball games requires the ability to produce extremely accurate coincident-timing behavior to make a motor response coincide with the arrival of an object at a designated point in space and time (Ripoll & Latiri, 1997). Moreover, McLeod et al. (1986) argued that in catching or striking a ball, the temporal window for a successful catch or hit is approximately 10 ms in baseball, cricket, and table tennis (Bahill & LaRitz, 1984; Bootsma & van Wieringen, 1990; Glencross & Cibich, 1977).

An alternative perspective based on cognition has attempted to explain movement behavior at a psychological level. A basic assumption is that information in the environment is perceived, and hypothetical internal processes are established within limits of the information processing capacity (Davids et al., 1994; Schmidt & Lee, 1999). According to this perspective, interceptive actions highlight the role of expert perception in decision-making, planning, and interceptive actions (Abernethy, 1987; Whiting, 1969). Successful interceptive actions are dependent on a series of complex computational differentiations involving brief glimpses of velocity and distance cues from the approaching ball's flight. These processes are related to past memories of similar events. Cognitive theorists account for timing behavior by suggesting that the observer derives time-to-contact from a number of physical variables during the objects' approach (Bruce et al., 1996; Gordon, 1989; Savelsbergh, 1990). These variables include distance, velocity, and size information derived from an object. Extensive experience in a situation allows the observer to develop an internal algorithm to compute the value of each variable while extrinsically timing an interceptive action. The computational approach requires knowledge about the size of the approaching object before perceived information about velocity and distance can be scaled into the algorithm for computing time-to-contact. The

observer computes time-to-contact by dividing the object's momentary distance from the eye by its current velocity (Tresilian, 1991). Knowledge about object size is acquired through specific experiences in particular performance settings and is symbolically represented in the memory component of information processing system. Thus, the more interceptive information that is stored in memory, the less error in anticipatory timing behavior.

When information about the ball's flight has been encoded, transformed, and perceived, a motor response can be selected from the stored repertoire of responses to intercept the ball (Tyldesley & Whiting, 1975). Tyldesley and Whiting proposed the operational timing hypothesis as a means by which experts reduce temporal uncertainty of interceptive actions by practicing until consistency is achieved. Thus, expert performers are faced with the problem of when to initiate the action with minimal visual information processing time.

Many experiments have reported that minimal visual information feedback time is available to performers (Carlton, 1981; Glencross & Barrett, 1992; Quinn & Sherwood, 1983). Although opinions differ as to the exact duration of feedback time required, most of these studies agree that a significant amount of time elapses between the visual presentation of a stimulus and the subsequent motor response. The minimal visual information processing time for simple reaction time in interceptive actions is about 200 ms. Thus, based on this notion, highly timed interceptive actions can be achieved by a refined motor program with a visual information processing time delay of approximately 200 ms.

However, these findings and explanations have been criticized for being too specific to laboratory contexts in which participants are required to react suddenly to the appearance of a visual signal. A clear distinction should be made between these specific constraints and typical timing conditions in real life situations in which performers modulate ongoing actions on the basis of continuously available information (Bootsma & van Wieringen, 1990; Whiting, 1991).

The methodological techniques used by the cognitive approach have been criticized for other reasons, including (a) problems with ecological validity of the experimental context, (b) an apparent obsession with reaction-time paradigms, (c) the failure to implement realistic movement response measures, and (d) the use of a static and small-scale stimulus display to present information (Davids et al., 1994; Williams et al., 1992, 1999). Moreover, in all such studies based on the information processing perspective, visual information has been conceived as the traditional interpretation of amount of uncertainty (Shanon & Weaver, 1959) rather than in terms of a lawful specification of events (Gibson, 1979). Arbitrary coupling has been arranged between the stimulus and response. Having to increase or reverse the speed of movement on the basis of a light coming on at some unpredictable moment during movement execution can not be compared with movement execution on the basis of continuous information flow specifying present and future positions of an object such as a ball.

Traditionally, there has been a tendency to focus on coincidence anticipation or motion prediction tasks in which participants typically have to report verbally when a suddenly occluded object or image arrives at a designated target. These paradigms emphasize perceptual anticipation processes, whereas in the study of natural interceptive

actions the emphasis is on receptor anticipation processes (Poulton, 1957; Tresilian, 1995; Williams et al., 1992, 1999).

In dynamic interceptive actions, participants are typically able to view a ball until contact is complete. There is ample opportunity for information to provide a catching, hitting or guiding role for action. The implication is that the typically distinct constraints of motion prediction and natural interceptive tasks may involve different control mechanisms. In natural interceptive actions, the execution times are far shorter than in motion prediction tasks. Also, a ball can be viewed during the whole approach flight. As evidenced by results on timing from ordinary people and infants, the large variability in estimation of time-to-contact typically reported in simulation studies is often not present in the performance of natural tasks such as rapid interceptive actions (Williams et al., 1999).

In fact, Bootsma (1988, 1989) demonstrated that the more natural realistic action yielded less variability of the response under similar optic flow patterns. Specifically, the more the required motor action was separated from a natural perception-action coupling, the less precise the timing response. Moreover, Tresilian (1995) argued that the variability (e.g., standard deviation of response times) of responses in coincidence anticipation tasks (e.g., unnatural link between perception and action such as button-press) is five or six times greater than those observed in interceptive actions performed under the same stimulus conditions. This finding calls into question the use of coincidence anticipation methods, such as film-based tasks, for investigating the timing of dynamic interceptive actions. Further, using unrealistic testing conditions to assess

dynamic interceptive actions in sport prevents performers from demonstrating the tight coupling between the perceptual and motor action systems.

In contrast to the cognitive perspective approach, the ecological approach to perception and action emphasizes the high quality of visual information continuously available for direct perception in the environment (Gibson, 1979). For this reason, information does not have to be embellished by inference with internalized models of the world or computational algorithms. A functional relationship between perceptual and action systems has evolved to support the behaviors involved in negotiating surfaces and interacting with objects in typical environments (Gibson, 1979).

A primary tenet of the ecological perspective approach is that ambient light arriving at the eye provides optical information for the performer. According to Gibson (1979), light reaches the eye after having been reflected off surfaces and objects in the environment and this information inherently contains structure. Light is reflected on the retina and exists in a highly structured distribution called an array. In ecological psychology, optic variables refer to the properties of the light reflected in a lawfully structured way. These properties are available to be perceived directly by all organisms equipped with a visual system. From an ecological perspective, the textured elements of the environment perturb the flow of light rays in meaningful ways for humans. The continuous availability of information for pick up by purposefully designed perceptual systems is an important element of ecological explanations of the performance of dynamic interceptive actions.

A second point in the ecological perspective is that of compensatory variability, exemplified in the study of dynamic interceptive actions by Bootsma and van Wieringen

(1990). The ability of experts to modulate precisely ongoing dynamic interceptive actions is predicated as a function of movement variability during interceptive actions.

Specifically, compensatory variability is a functional type of variability. A critical way that skilled performers in dynamic environments produce a tight coupled fit between the current state of the action system and the task's goal. This occurs from of all important endpoint of execution, through modulating movements on the basis of ongoing perceptual information. Bootsma and van Wieringen suggested that action systems and perceptual systems could be used to compensate for sudden changes through the covariation of movement duration and initiation time for an interceptive action. Such variability between trials should be viewed as compensatory. When an interceptive action was broken up into two submovement parts, the higher negative correlations for the first part with mean speed suggested that adaptations were taking place from trial to trial.

Evidence for intra-trial variability was also provided by Bootsma and van Wieringen (1990). Smaller movement variability as estimated by the coefficient of variation was found during the middle to late components of the interceptive actions, not the earliest part. According to the authors, this indicated that subjects were still altering their movements during the execution. The visual-motor delays of 105-122 ms observed in four participants suggested that they were still able to pick up movement-regulatory information at a relatively late stage of table tennis performance (Bootsma & van Wieringen, 1990). Consequently, the results contradicted traditional information-processing findings in that experts rely on the known duration of an interceptive action with consistent motor programs for an interceptive action, in which visuomotor delay is limited by 200 ms (Abernethy, 1981; McLeod, 1987; Tyldesley & Whiting, 1975).

Indeed, Bootsma and van Wieringen (1990) criticized studies as artificial that reported visual motor delays of around 200 ms.

Based on the ecological perspective, the most well-known control variable for interceptive timing movements is tau (Lee, 1980; Turvey & Carello, 1986). Lee (1976) demonstrated that as an object approaches, visual information is specified by the relative rate of dilation of the closed optical contour. Theoretically, tau is visually available and does not involve prior measurement of speed, distance, or acceleration. According to Lee, because tau requires no complex computation, this approach supposes that information required for accurate perception of the world is entirely present in the stimulus so that the additional information from memory or other computational processes are unnecessary for understanding perception (Gibson, 1966, 1979; Turvey & Carello, 1986).

Supportive findings favoring tau have been frequently reported (Bootsma & van Wieringen, 1990; Davies & Green, 1990; Lee, 1980; Lee and Raddish, 1981; Wagner, 1982). Further, neural mechanism evidence for the visual system has helped to explain an interceptive timing. Wang and Frost (1992) reported that specific neurons in the brain respond with heightened electrical activity at a constant time before contact during perception of information from looming objects. The maximum response of the neuronal cells always occurs at a constant time-to-contact, regardless of changes in size and speed of the approaching stimuli. These findings are interpreted as suggesting a particularly simple account of how interceptive timing behaviors are performed.

However, recent studies have identified incongruent evidence concerning the tau hypothesis explanation (Lacquaniti, Carozzo, & Borghese, 1993; Tresilian, 1990, 1993, 1994, 1999; Wann, 1996). Tresilian argued that this proposition is deceptively simple,

and most tau-based studies are not fully valid and correct (Tresilian, 1997, 1999).

Because the tau-hypothesis is based on a constant-velocity approach, the estimate of actual time-to-contact, provided by tau can only be exact when the rate of approach between the observer or actor and the approaching object or surface is constant. However, constant approach velocities are rare in nature. In particular, when an object is accelerating toward an observer (or vice versa) tau typically overestimates actual time-to-contact, whereas under conditions of deceleration tau underestimates actual time-to-contact (Tresilian, 1991, 1995, 1999; Wann, 1996).

Other studies questioning the tau-hypothesis have noted that when careful observation is made of interceptive action, the action is not initiated at fixed value of time-to-contact. Instead, it has been repeatedly observed that movements are initiated earlier and take a longer time to execute when the target is moving slowly. They are initiated later and executed more quickly when the target moves faster (Bootsma & van Wieringen, 1990; Brenner & Smeets, 1994; Laurent, Montagne, & Savelsbergh, 1995; Wallace, Stephenson, Weeks, & Kelso, 1992).

In addition, Deluca and Warren (1994) reported that the size-arrival effect of object was found in earlier initiation time for large objects compared to smaller objects despite the use of equal distance and velocity in a computer simulation study. This finding implies that time-to-contact can be provided by the optical variable tau. However, tau is not the only means by which performers can perceive information for interceptive timing.

Two potential causes of the above stated conflicting results are: (a) failure to control the input variable tau and (b) failure of performance analysis on the basis of

continuously available visual information. Specifically, confounding effects from multiple sources of visual information; known distance between object and contact point, object size, and relative disparity information between object and performer in a case of full light, fixed distance, and object size. Thus, these possible sources of information may trigger different processing pathways (i.e., perceptual anticipation process: cognitive perception). An additional concern is the low ecological validity inherent in tasks such as key pressing or simple catching performance. These limitations should be addressed when an experiment on interceptive action study is designed. Indeed, when a performer catches a ball from different heights in real situations, multiple sources of visual information are available and can affect the outcome of interceptive timing performance characteristics (i.e., kinematics of catching movement).

Despite these potential confounding effects from multiple sources of visual information and unnatural experimental settings, no study has controlled the multiple sources of visual information. Therefore, to determine a valid reading about whether tau is used in interceptive timing tasks, only tau should be provided in the experimental situation with control of distance perception of visual information (i.e., blocking perceptual anticipation from absolute and relative disparity, known ball size, and drop distance).

Thus, the aim of Experiment 1 was to examine whether tau can be used as a control variable source of visual information in an interceptive timing task in a gravitational acceleration context. To accomplish this purpose, a one-handed catching task with different ball drop heights and ball sizes was tested in a totally dark room condition with only right eye monocular vision. Randomized trials were applied to

prevent any other confounding effects while maintaining a real situation of ball catching as much as possible. Participants were able to use only the approaching ball image information during ball drops. No visual information about ball size or ball drop height was provided prior to a ball drop. Thus, participants had to rely only on an optical expansion image of the luminescent dropping ball. Three dimensional kinematic data of the index finger and thumb movements involved in the catching task were collected for a full analysis of catching performance.

The specific question addressed in Experiment 1 was: Can tau be used as a control variable for an interceptive timing task based on continuously available optical information in gravitational acceleration? If tau is used as a control variable for an interceptive timing task, then the research hypotheses predicted that: (a) the moment of closing the index finger and thumb action start at the same moment as the dropping ball, (b) the maximum aperture size was affected by the ball sizes, and (c) the compensatory variability (i.e., readjustment process from moment of opening to moment of opening and ball catch) occurred during the ball catching action.

Method

Participants

Ten male graduate students with normal or corrected-to-normal vision (contact lenses only), ages 26 - 33 (mean age = 28.5 years old) participated. All participants were dominant right-handers as determined by a modified version of Edinburgh Handedness Inventory (Oldfield, 1971).

Experimental Set-up and Instruments

Attached to a 5 m vertical pole were three 1.5 m horizontal bars. Three different heights (2.4 m, 3.4 m, and 4.4 m) were used for the different ball-drop heights. Three electromagnetic solenoid devices (ball holders) were attached to each horizontal bar at 1 m, 1.2 m, and 1.4 m positions. The electromagnetic device was controlled by a switch that was connected to the computer. The moment that the on-off switch was pressed and registered in the computer defined the moment of ball release.

Two balls with different diameters (5.5 cm and 6.5 cm) were used as the catching target objects. The balls were painted with luminous paint so that they could be seen in the dark room condition. The luminescent balls were charged in a light box and the brightness of the ball was kept constant. A small round-shaped metal piece (0.2 cm diameter) was attached to the ball's surface so that it could be attached to electromagnetic device. When the electromagnet device switch was off, the ball was released instantaneously. On the palm of catching hand, a small square-shaped microswitch (2 cm diagonal) was placed on a contact point. This switch signal provided ball-hand contact time and was automatically recorded by the computer. This instant was used as the temporal reference point for the catching hand.

To prevent participants from previewing the initial position of the ball, a pair of liquid crystal display (LCD) goggles were used. The goggles changed from opaque to transparent (or vice versa) with a rise time of 5 ms. Optimal synchronization of the opening of the goggles and the electromagnetic device switch was ensured by interconnection with the computer. The on-off signal for the goggles was transmitted to the computer for determining the timing sequences.

The heights for ball-drop (2.4 m, 3.4 m, 4.4 m) were determined by measuring the vertical distance from the bottom of the hanging ball and the ball contact point on the palm of the right hand. The duration of the ball drop from the three different heights was calculated by the equation for the constant gravitational acceleration. However, to secure the valid experimental set-up of each condition, the duration of ball drop in each condition were measured by using an Acknowledge Data Acquisition system with 1000 Hz sampling rate and compared with the simulated ball drop data. The ball-drop simulation duration times were 700 ms (2.4 m), 832 ms (3.4 m), and 947 ms (4.4 m).

To begin testing, participants laid down on a platform and their visual gaze was vertically aligned with a suspended ball. The right wrist rested on a wrist pad and Velcro straps secured a constant position. To capture the 3D real-time kinematic data of two fingers movement during ball catching, an electromagnetic tracking (EMT) system was used. The EMT hardware was a 6D RESEARCH system (Skill Technologies Inc.) using FASTRACK sensors (Polhemus, Inc.). The motion capture unit (MCU) of the 6D system contains hardware and software to control and digitize the electromagnetic signals. A transmitter contained three mutually orthogonal coils (solenoids), and generated three different electromagnetic flux in the three different fields. The magnetic flux generated proportional currents used to calculate a vector signifying the direction and strength of magnetic field at the site of the sensor.

The two FASTRACK sensors were attached to the index finger (centered on the nail surface) and to the thumb. This was accomplished with double-sided tape and the sensor cables were strapped on the wrist. The 6D research software computed 6 degrees of freedom position (x, y, and z coordinates) and orientation (yaw, pitch, and roll) of

tracking the sensors. This software was used to capture kinematic data of the index finger as well as thumb movement coordinates. Appendix D provides a schematic diagram of the apparatus.

Procedures

At the beginning of a testing session, participants were given the handedness questionnaire, confirmed right-handedness, and they signed an informed consent agreement. Two FASTRACK sensors were attached on the finger nail surface of the index finger and thumb. The contact point of the right hand was aligned directly perpendicular to the ball-drop's path. As participants were positioned on the experimental apparatus, they put on the LCD goggles and maintained this inclined position throughout testing. The left side of the goggles was covered with a black patch so that only right eye was visible. Participants received a ready signal and approximately 1 to 3 s later the shutters of the goggles were opened (i.e., became transparent), and 500 ms later the ball was released by switching off the electromagnet. The periods between the ready signal and shutter opening of the goggles were randomly varied from 1 to 3 s to reduce the possibility of anticipatory movements. To maintain the constant time period of 500 ms between shutter opening and ball release, an adjustable time delay switch were used for the constant delay control.

To minimize any possible sound cues from the switch operation (i.e., clicking sound of the on-off switch), participants wore earphones and heard low level white noise (60 dB). Participants had no eye movement restrictions once the goggles were opened and they were instructed to catch the dropping ball as accurately as possible. The ready position of the two fingers was closed the thumb and index finger were put together,

before the ball was released. To familiarize the participants with the experimental setting and task in each condition before testing began, five practice trials were provided in a totally dark room with only the luminous ball visible. Once the testing began, participants completed 15 trials in the six conditions (two ball sizes and three ball-drop heights). A total of 90 trials were administered. Conditions were presented randomly trial by trial. After 30 trials, participants were given a 3 min of rest. A detailed graphical illustration of the procedures is shown in Appendix D.

Dependent Measures

All kinematic measures were computed from the 3D coordinates (x-axis: anterior-posterior; y-axis: medial-lateral; z-axis: inferior-superior) collected for each ball-size and ball drop height condition. Based on displacement data of the movement of the two fingers, relative velocity and acceleration were calculated by the central difference method. The kinematic measures in Experiment 1 were collected from the sensors with data sampled at 120 Hz and filtered using a 6 Hz low-pass digital butterworth filter.

The dependent measures were determined by following standardized procedures. For this purpose, the moment of ball and hand contact was determined by the ball contact switch on the center of the palm. All timing measures were defined with respect to the moment of ball contact with the palm switch. Therefore, a negative time indicated an event occurred before ball catch and hand contact, and a positive time indicated an event occurred after ball hand contact. Seven dependent measures were operationally defined during the catching action.

- (1) Moment of opening (ms): the initiation time for opening (spreading motion) the index finger and thumb relative to the instant of ball and hand contact.

Onset time of the opening was measured from the point at which the relative velocity changed to a positive value for the index finger and thumb movements.

- (2) Maximum aperture size (cm): the maximum distance between the index finger and thumb prior to catching a ball.
- (3) Peak opening velocity (cm/s): the peak relative velocity of the rate of increase as the index finger and thumb are opened to maximum aperture.
- (4) Moment of closing (ms): the initiation time for closing the index finger and thumb relative to the instant of ball and hand contact. Onset time of this closing motion (grasp) was measured from the point that the index finger and thumb relative velocity changed to a negative value.
- (5) Peak closing velocity (cm/s): the peak relative velocity of the rate of decrease in aperture while the hand is readying for a catch (grasp).
- (6) Moment of ball catch (ms): the moment of ball catch by the index finger and thumb. Time to ball catch was measured from the point at which the relative velocity changed from a negative to a positive value of index finger and thumb movements.
- (7) Variability scores: the standard deviation of the moment of opening, closing, and ball catch.

A detailed illustration of how the dependent measures were calculated for a trial is shown in Appendix D.

Results

For each participant, means and standard deviations in each condition were calculated for all dependant variables. Data were analyzed in a 2×3 (Ball Sizes: 5.5 and 6.5 cm diameter \times Ball Drop Heights: 2.4 m, 3.4 m, and 4.4 m) multivariate analysis of variance (MANOVA) with repeated measures on both factors. All significant MANOVA effects as indicated by Wilks' Lambda were further analyzed in separate 2×3 (Ball Sizes: 5.5 and 6.5 cm diameter \times Ball Drop Heights: 2.4 m, 3.4 m and 4.4 m) univariate ANOVAs with repeated measures on both factors. Additionally, variability measures (standard deviations) for the moment of opening, closing, and ball catch were analyzed in a $2 \times 3 \times 3$ (Ball Sizes: 5.5 and 6.5 cm diameter \times Ball Drop Heights: 2.4 m, 3.4 m and 4.4 m \times Catching Phase: Opening, Closing, and Ball Catch) MANOVA with repeated measures on the three factors. Alpha was set at 0.05 for all tests. Scheffe's post hoc analysis revealed exact locations of effects.

MANOVA results for the mean performances of the dependent measures revealed significant main effects for both ball drop height, $F(12,26) = 6.36$, $p < .001$, Wilks' Lambda = 0.0645, and ball size, $F(6,4) = 16.3$, $p < .001$, Wilks' Lambda = 0.038552. There was no significant interaction between the two factors $F(12,26) = 0.86$, $p = .59$, Wilks' Lambda = 0.512. Further, analysis of the standard deviations of the six dependent measures failed to reveal significant effects for ball drop height, $F(12,26) = 1.76$, $p = .11$, Wilks' Lambda = 0.3041, ball size, $F(6,4) = 0.90$, $p = .56$, Wilks' Lambda = 0.4242, or balldrop height by ball size interaction, $F(12,26) = 0.66$, $p = .77$, Wilks' Lambda = 0.5894. Appropriate univariate repeated measure ANOVAs are reported for the individual ball catching dependent measures.

Moment of Opening

Table 2.1 reports the means and the standard deviations for the moment of opening the index finger and thumb. As seen in Figure 2.2, the moment of opening the thumb and index finger movement started earlier as the ball drop height decreased. The univariate analysis revealed a significant main effect for ball drop height, $F(2,18) = 20.04$, $p < .001$. Scheffé's procedure indicated that the 4.4 m ball drop height started later than the 2.4 m and 3.4 m ball drop heights. However, no significant findings were identified for ball size, $F(1,9) = 0.01$, $p = .93$ or the interaction of Ball Drop Height \times Ball Size, $F(2,18) = 0.61$, $p = .55$.

Table 2.1 Means and standard deviations for the moment of opening (ms) as a function of ball height and ball size.

Ball Size	Ball Drop Height		
	2.4 m	3.4 m	4.4 m
	<u>M</u> (<u>SD</u>)	<u>M</u> (<u>SD</u>)	<u>M</u> (<u>SD</u>)
Large	-269 (27)	-251 (26)	-228 (19)
Small	-263 (22)	-253 (30)	-231 (23)

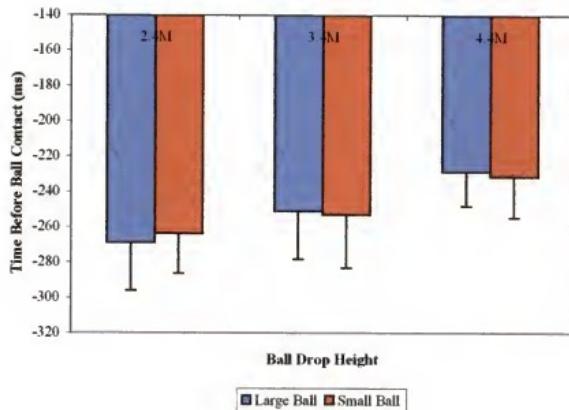


Figure 2.1 Mean and standard deviation bars for the moment of opening hand as a function of ball drop height and ball size.

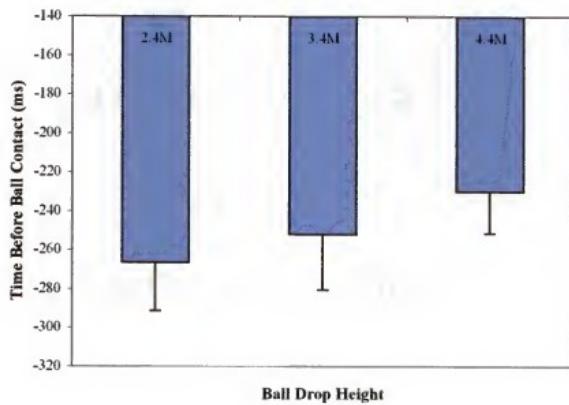


Figure 2.2 Mean and standard deviation bars for the moment of opening hand as a function of ball drop height.

Maximum Aperture Size

Table 2.2 presents the means and the standard deviations for the maximum aperture size of the index finger and thumb. Clearly, the maximum aperture size increased as ball size increased (from 10.5 cm to 11.4 cm), resulting in a significant main effect for ball size, $F(1,9) = 112.11$, $p < .001$. Figure 2.4 shows the ball size main effect. No significant effect for ball drop height, $F(2,18) = 1.48$, $p = .25$, or the two-way interaction, $F(2,18) = 0.58$, $p = .57$, were found.

Table 2.2 Means and standard deviations for the maximum aperture size (cm) as a function of ball height and ball size.

Ball Size	Ball Drop Height		
	2.4 m	3.4 m	4.4 m
	<u>M</u> (<u>SD</u>)	<u>M</u> (<u>SD</u>)	<u>M</u> (<u>SD</u>)
Large	11.09 (0.8)	11.36 (1.2)	11.61 (1.0)
Small	10.38 (0.9)	10.54 (1.1)	10.75 (1.1)

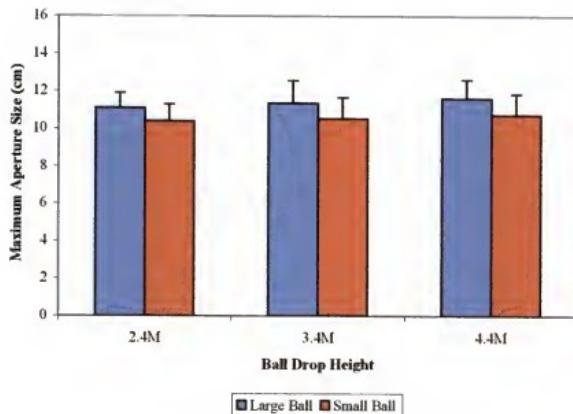


Figure 2.3 Mean and standard deviation bars for the maximum aperture size as a function of ball drop height and ball size.

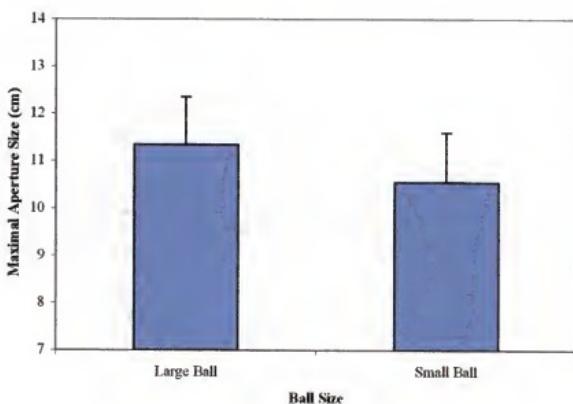


Figure 2.4 Mean and standard deviation bars for the maximum aperture size as a function of ball size.

Peak Opening Velocity

The means and the standard deviations for the peak opening velocity dependent measure are presented in Table 2.3. Univariate analysis yielded a significant main effect for ball drop height, $F(2,18) = 6.63$, $p < .01$. Scheffe's procedure indicated a higher peak opening velocity for the 4.4 m ball drop height than for the 2.4 m or 3.4 m ball drop height conditions. No significant differences were found for ball size, $F(1,9) = 0.48$, $p = .50$ or Ball Drop Height \times Ball Size, $F(2,18) = 1.24$, $p = .31$. See for Figure 2.5 and 2.6 for graphic depictions of the ball drop height effect.

Table 2.3 Means and standard deviations for the peak opening velocity (cm/sec) as a function of ball height and ball size.

Ball Drop Height			
Ball Size	2.4 m	3.4 m	4.4 m
	M (SD)	M (SD)	M (SD)
Large	63.82 (12.8)	65.05 (14.1)	75.04 (10.5)
Small	61.62 (13.8)	61.70 (14.4)	76.74 (09.4)

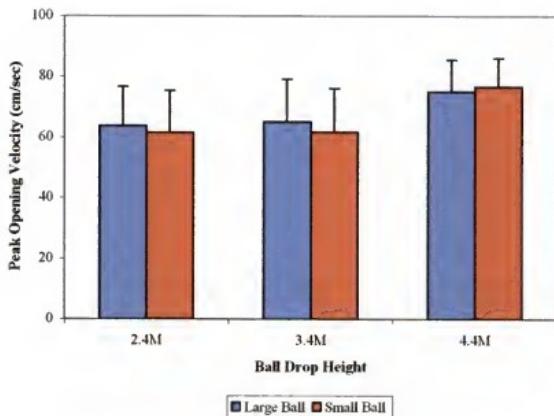


Figure 2.5 Mean and standard deviation bars for the peak opening velocity as a function of ball drop height and ball size.

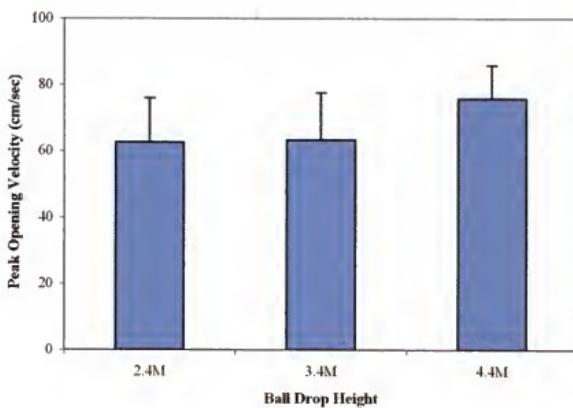


Figure 2.6 Mean and standard deviation bars for the peak opening velocity as a function of ball drop height.

Moment of Closing

Table 2.4 lists the means and standard deviations for the moment of closing the fingers. Interestingly, the moment of closing finger and thumb movements showed no differences across the different ball drop height and ball size conditions. Analysis of the moment of closing data failed to reveal significant effects: (a) ball drop height, $F(2,18) = 2.62$, $p = .1$, (b) ball size, $F(1,9) = 0.26$, $p = .62$, or (c) interaction, $F(2,18) = 1.05$, $p = .37$. These findings indicated that the moment of closing finger movement did not change across the different ball drop heights or the ball sizes.

Table 2.4 Means and standard deviations for the moment of closing (ms) as a function of ball height and ball size.

Ball Size	Ball Drop Height		
	2.4 m	3.4 m	4.4 m
	<u>M</u> (<u>SD</u>)	<u>M</u> (<u>SD</u>)	<u>M</u> (<u>SD</u>)
Large	-38 (8)	-32 (10)	-35 (9)
Small	-37 (7)	-35 (09)	-34 (8)

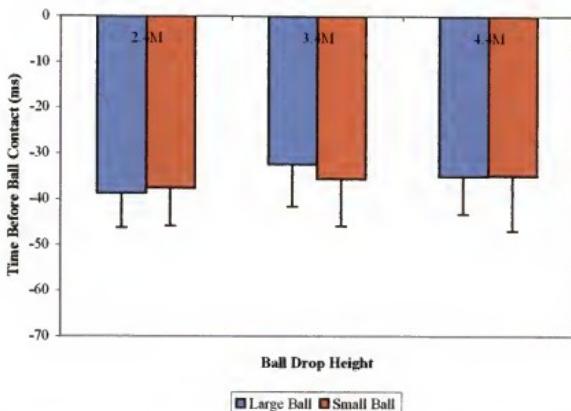


Figure 2.7 Mean and standard deviation bars for the moment of closing hand as a function of ball drop height and ball size.

Peak Closing Velocity

The means and the standard deviations for the peak closing velocity of the index finger and thumb are displayed in Table 2.5. The maximal closing velocity increased as the ball drop height increased. Univariate analysis revealed significant main effects for the ball drop height, $F(2,18) = 9.71$, $p < .001$. Scheffe's procedure revealed that the peak closing velocity was faster for 4.4 m ball drop height than for 2.4 m and 3.4 m condition. Furthermore, as ball size was decreased, the peak closing velocity increased, resulting in a significant main effect of ball size, $F(1,9) = 8.23$, $p < .001$. No significant interaction was found, $F(2,18) = 1.65$, $p = .21$. See Figures 2.8, 2.9, and 2.10 for graphic representations of the peak closing velocity.

Table 2.5 Means and standard deviations for the closing velocity (cm/sec) as a function of ball height and ball size.

Ball Size	Ball Drop Height		
	2.4 m	3.4 m	4.4 m
	<u>M (SD)</u>	<u>M (SD)</u>	<u>M (SD)</u>
Large	-48.89 (18.1)	-52.73 (17.9)	-73.21 (18.5)
Small	-57.12 (19.9)	-53.25 (18.6)	-74.80 (19.4)

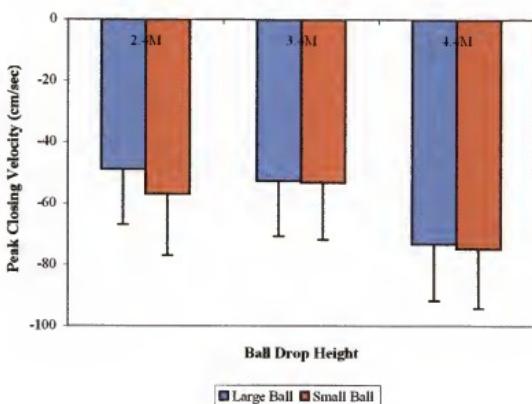


Figure 2.8 Mean and standard deviation bars for the peak closing velocity as a function of ball drop height and ball size.

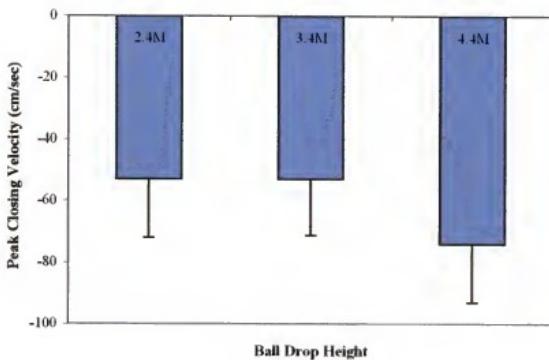


Figure 2.9 Mean and standard deviation bars for the peak closing velocity as a function of ball drop height.

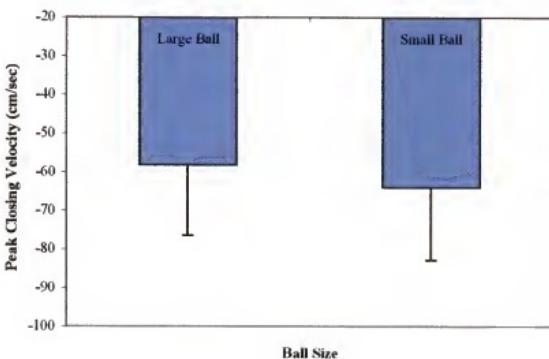


Figure 2.10 Mean and standard deviation bars for the peak closing velocity as a function of ball size.

Moment of Ball Catch

Data for the moment of the ball catch are displayed in Table 2.6. The 2×3 repeated measures ANOVA revealed two significant main effects: (a) ball size, $F(1,9) = 30.36$, $p < .001$, and (b) ball drop height, $F(2,18) = 66.06$, $p < .001$. As seen in Figure 2.12, for the ball size main effect, a small ball was caught later as compared to the large ball. For the ball drop height main effect, the higher ball drop displayed an earlier ball catch. See Figure 2.13, for the main effect of ball drop height. Scheffe's procedure indicated that the earlier ball catch was made in the 4.4 m ball drop height than in the 3.4 m and the 2.4 m ball drop height. The interaction term failed significance, $F(2,18) = 1.58$, $p < .23$.

Table 2.6 Means and standard deviations for the moment of ball catch (ms) as a function of ball height and ball size.

		Ball Drop Height		
Ball Size		2.4 m	3.4 m	4.4 m
	<u>M (SD)</u>	<u>M (SD)</u>	<u>M (SD)</u>	<u>M (SD)</u>
Large	145 (5)	139 (6)	131 (5)	
Small	152 (3)	146 (6)	135 (6)	

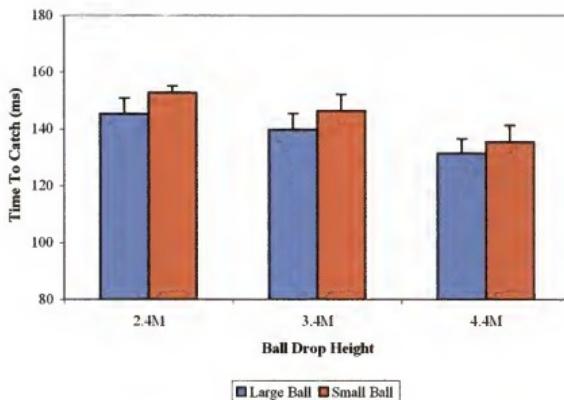


Figure 2.11 Means and standard deviation bars for the moment of ball catch as a function of ball drop height and ball size.

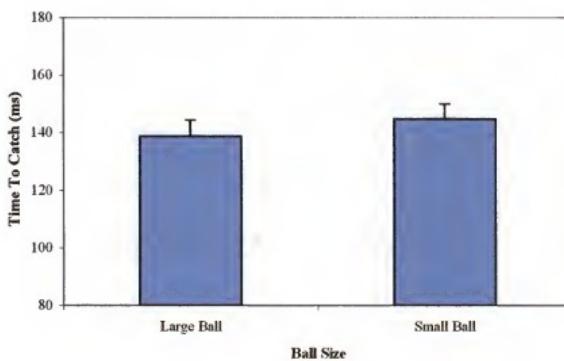


Figure 2.12 Means and standard deviation bars for the moment of ball catch as a function of ball size.

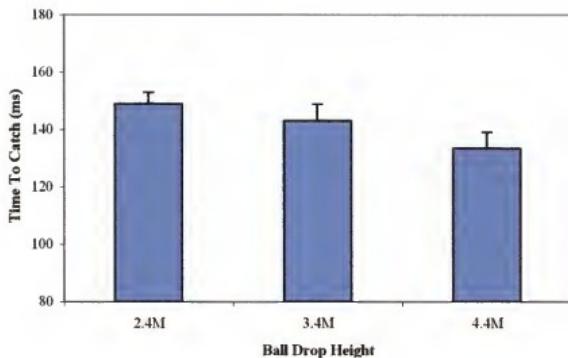


Figure 2.13 Means and standard deviation bars for the moment of ball catch as a function of ball drop height.

Variability Score for the Opening, Closing, and Ball Catch Movement Phases

Table 2.7 presents the means and the standard deviations for the variability score of each movement phase. The MANOVA procedure revealed a significant main effect for the moment phase, $F(2,18) = 74.28$, $p < .001$, Wilks' Lambda = 0.1080. Scheffe's procedure showed that the variability score of the moment of the opening phase was larger than that of the moment of closing or ball catch. That is, timing variability was larger when the index finger and thumb were started at the moment of the opening phase. However, timing variability decreased as the index finger and thumb move toward the moment of the closing and ball catch.

No significant effects were found for ball size, $F(1,9) = 3.92$, $p = .07$, Wilks' Lambda = 0.6965, ball drop height, $F(2,18) = 0.83$, $p = .45$, Wilks' Lambda = 0.9151, or the interactions (Ball Drop Height \times Ball Size: $F(2,18) = 0.49$, $p = .61$, Wilks' Lambda = 0.9482; Ball Drop Height \times Movement Phase: $F(4,36) = 1.74$, $p = .16$, Wilks' Lambda = 0.8379; Ball Size \times Movement Phase: $F(2,18) = 0.11$, $p = .89$, Wilks' Lambda = 0.9874; Ball Drop Height \times Ball Size \times Movement Phase: $F(4,36) = 0.66$, $p = .62$, Wilks' Lambda = 0.9316). Figures 2.14 and 2.15 show these data.

Table 2.7 Means and standard deviations for the variability score (ms) as a function of finger movement phase, ball drop height, and ball size.

Condition		Moment of Finger Movement Phase		
		Opening	Closing	Catch
		M (SD)	M (SD)	M (SD)
2.4 m	Large Ball	26.4 (11.1)	7.9 (1.9)	6.3 (1.8)
	Small Ball	28.1 (7.80)	10.2 (4.7)	8.8 (2.7)
3.4 m	Large Ball	31.4 (8.70)	6.8 (2.9)	7.7 (3.0)
	Small Ball	38.2 (9.80)	8.5 (4.5)	8.1 (2.6)
4.4 m	Large Ball	34.2 (14.0)	8.4 (2.6)	6.3 (2.4)
	Small Ball	33.4 (13.7)	9.0 (3.4)	8.0 (3.4)

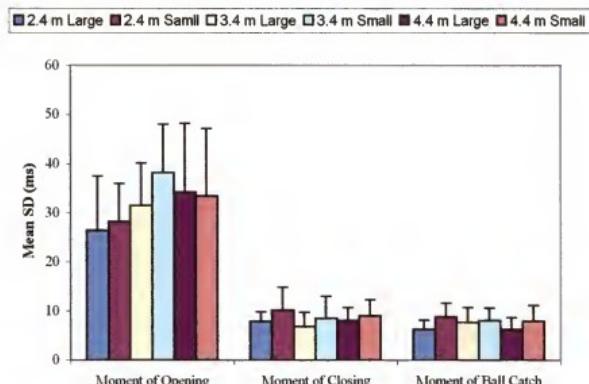


Figure 2.14 Mean and standard deviations bars of the variability score for the movement phase as a function of ball drop height and ball size.

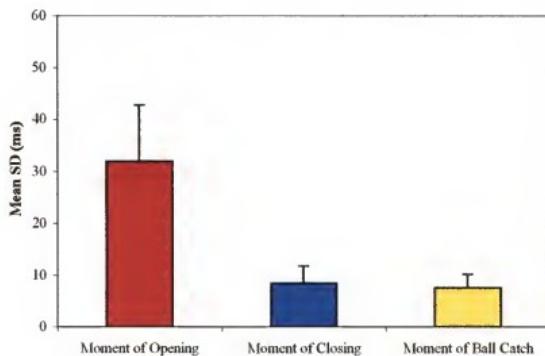


Figure 2.15 Mean and standard deviation bars of the variability score as a function of the movement phase.

Discussion

Experiment 1 was conducted to examine the role of tau as a control variable for one-handed catching in gravitational acceleration. Participants were asked to perform ball catches with two different ball sizes and three different ball drop heights. Significant kinematic results of the index finger and thumb movements of one-handed ball catching are discussed and conclusions about tau are drawn.

The findings support the research hypotheses, and are consistent with previous studies (Lee et al., 1983; Savelsvergh et al., 1992, 1993; Savelsbergh & van der Kamp, 2000; van der Kamp, et al., 1997). That is, the moment of closing two fingers (index finger and thumb) did not change across the different ball drop heights and ball sizes. From an ecological perspective, the pattern of optical expansion, brought about by the relative approach between an object in the environment and an actor, provides predictive temporal information of time-to-contact. That is, the remaining time-to-contact is directly specified by the inverse of the relative rate of dilation of the closed optical contour of the approaching object, generated in optical array. Therefore, if this type of optical information is used for controlling timing tasks continuously during movement execution, the moment of initiation of action (e.g., catching, hitting, or grasping) should be started at the same time regardless of the size of the object or the speed of the approaching object. These findings support tau's prediction for an interceptive timing task.

Concerning the cognitive theoretical standpoint, a possible strategy would be for participants to initiate the catching movement of the fingers at some critical threshold when the ball is at a certain distance away from the contact point (i.e., a palm of hand). However, such a strategy places all the emphasis on the perceived input variables such as

computational differentiation from distance perception and ball size, consistently being able to initiate their action at an optimal point in time. To examine the possibility that participants make use of such a strategy, the timing data at the moment of closing was converted into distance data. These data were compared across conditions. However, no support was found that the different ball drop heights or ball sizes were different at the moment of closing the index finger and the thumb movements varied across the condition. This indicates that the interceptive timing action was not controlled with the perceived distance information between ball and contact point.

Another finding focused on the differences of maximal aperture size between the small ball and large ball. For the ball size conditions, the actual size difference between two balls was 1 cm in diameter (respectively 5.5 cm and 6.5 cm). The small ball showed a smaller maximal aperture size, a higher peak closing velocity, and a later moment of ball catch than the large ball size condition. Furthermore, the size differences between the two ball sizes were reflected directly to the maximal aperture size of the finger movements. These findings were in accordance with a number of previous findings in the literature on reaching and grasping movements (e.g., Savelsbergh et al., 1991; van der Kamp et al., 1997; Von Hofsten, 1988). Further, the earlier moment of ball catch for the large ball is a reflection of the shorter closing distance the fingers required to cover for the large ball than for the small ball. Similarly, the significantly higher peak closing velocity for the small ball condition confirms the prediction. That is, the higher peak closing velocity and the later moment of initiation of the ball catch phase for the small ball are complimentary consequences for the greater distance the fingers have to move to catch the small ball.

With respect to ball drop heights, the higher ball drop yielded higher peak opening and closing velocities than the lower ball drop. The earlier moment of ball catch was made under the higher ball drop condition. These findings suggest that closing the index finger and thumb are coupled with ball drop speed because the higher ball drop yielded a faster speed. Therefore, the peak opening and closing velocity of the fingers movement were highly coupled with ball drop speed. This result is consistent with numerous previous ball catching studies (Bootsma & van Wieringen, 1990; Carnahan & McFadyen, 1996; Fayt et al., 1997; Savelsbergh et al., 1992; Smeets & Brenner, 1995; van Donkelaar et al., 1992). For these studies, participants had to catch or hit, grasp objects rolling down a ramp, or had to intercept targets on a screen using a tool. In spite of the differences between the tasks, a consistent finding was the adaptation of the movement velocity to the speed of the approaching ball (Li, 1995; Li & Laurent, 1994, 1995). This coupling of the velocity between movement execution to the speed of the stimulus was denoted as intensity coupling by Li and Laurent (1995). The current findings indicate that such coupling can be interpreted as reflecting an influence of perceived speed of approach on the organization of movement based on continuously available optical information.

Another important finding was provided in the comparison of the variability score during the moment of opening, closing, and ball catch. The moment of opening produced higher variability in timing than the moment of closing or ball catch. Specifically, at the moment of opening, the index finger and thumb showed higher variability in timing. However, as the hand movements approached the final moment of the task goal (ball catch), the timing variability decreased with less than 8 ms variability (more than a 300%

decrease in comparison with the moment of opening). This result confirms Bootsma and van Wieringen's table tennis findings that the adaptive functional movement variability pattern was identified in the context of time-to-contact.

Similarly higher variability was found in the back-swing duration of experienced field hockey players (Burgess-Limerick et al., 1991) and the volleyball spike (Sardinha & Bootsma, 1993). In these studies, the highly variable inter-trial measurement of the hand and shoulder velocity, acceleration, and phase duration at the start of action was dramatically decreased at the critical point of ball/hand contact with highly consistent values. Bootsma and Peper (1992) have named this pattern of action a funnel-shaped control strategy. The current findings of the present study showed the identical pattern of variability. This indicates that the same type of control strategy was applied in the current ball catching movement of the index finger and thumb.

In conclusion, the present results strongly indicate that the optical variable tau is used as a control variable for interceptive timing action under monocular vision and a totally dark environment. Based on the expanding optical visual information of an approaching ball, participants process the visual interceptive timing information until a late stage of the ball catching. The notion of the continuous perception-action coupling for interceptive timing conceptualized from an ecological perspective showed more valid explanation power than the notion of the cognitive perspective.

CHAPTER 3 EXPERIMENT II

One-Handed Ball Catching with Vision and Environment Constraints

Based on the tau hypothesis for an interceptive timing task such as ball catching, visual information related to the optical expansion rate of the retinal image by an approaching ball is used to regulate the anticipatory timing (Lee, Young, Reddish, Lough, & Clayton, 1983; Savelsbergh, Whiting, & Bootsma, 1991; van der Kamp, Savelsbergh, & Smeets, 1997). In this explanation, information about time-to-contact should be equally accessible to one eye as to two, and interceptive timing performance under monocular and binocular conditions should be equivalent. However, recent studies have indicated that anticipatory timing performances are superior for a binocular condition compared to a monocular condition.

McLeod et al. (1986) examined monocular versus binocular issues in cricket. The ball hitting performance was assessed for the percentage of successful hits in a task without spatial uncertainty. No difference was found between the monocular and binocular viewing conditions. However, for the only temporal uncertainty case, the percentage of successful hits was only one aspect of performance. Therefore, the difference between binocular and monocular vision for the interceptive timing action is undeterminable without detailed kinematic analysis of interceptive timing action.

A similar study was conducted by Abernethy and Crassini (1989) for a coincidence-timing task with no spatial uncertainty. Apparent motion of between 2.24

m/s (5 mph) and 8.94 m/s (20 mph) was presented to participants down a 4.30 m runway and they were required to make a thumb-press response to coincide with the objects' arrival at the end of the runway. Participants in the monocular viewing condition were consistently late compared to the binocular viewing condition. The authors argued that the deprivation of binocular disparity information caused participants to overestimate time-to-contact. Moreover, van Hofsten et al. (1992) reported consistent results with Abernethy and Crassini's findings that catching performance under the binocular condition was superior to the monocular condition.

Even though these results from monocular versus binocular studies showed differences in time involved in the catching performances, the findings are not conclusive because the interceptive timing task in previous studies used a button-press response, and failed to provide a natural coupling between perception and action. Therefore, the contribution of optical information in a button-press anticipation task may be different from a real interceptive timing action such as ball catching. Thus, the interceptive timing may revealed different performances with different task constraints (Bootsma, 1989; von Hofsten, 1987).

In addition, with respect to binocular and monocular viewing conditions, absolute and relative disparity can be separated (Regan, 1992). Absolute disparity is defined as the difference between the optical angle subtended by the nodal point of the two eyes at the object and angle subtended by the rotation centers of the eyes at the fixation point. Therefore, absolute disparity information is available in the binocular vision only condition. On the other hand, relative disparity is equal to the difference between the projections of the two textured elements on the retina. In a totally dark room, only the

ball is visible so that there is no relative disparity information. However, the background surface in a fully lighted room provides relative disparity information. Given that a majority of the monocular and binocular studies have been conducted in dark room conditions, the question still remains whether relative disparity is involved in interceptive actions. Further, does relative disparity contribute to improved interceptive actions found in catching studies conducted in a light room environment?

The results of Experiment 1 demonstrated that the optical variable tau was used as a control variable for the interceptive timing actions. However, the use of tau should be applied only for the restricted condition (i.e., only optical expansion image of the approaching ball available) because only monocular vision was available and the ball catching task was administered in a totally dark environment.

The aim of Experiment 2 was to examine whether interceptive timing actions are solely controlled by the optical variable tau or whether another source of visual information received from the environmental setting (i.e., light versus dark) and viewing condition (i.e., binocular versus monocular) contributes to successful interceptive timing movements of the index finger and thumb. The tau hypothesis predicts a constant time-to-contact strategy and no differences in the timing of a ball catching action are expected when environmental structure and/or binocular vision are provided or removed. However, if environmental structure and/or binocular vision both influence interceptive timing actions, manipulation of these visual information sources may result in systematic deviations in the various kinematic measures from a constant time-to-contact strategy.

Method

Participants

Ten male graduate students with normal or corrected-to-normal vision (contact lenses only), age 25 - 32 years (mean age = 26.4 years old), volunteered. All participants were dominant right-handers as determined by a modified version of Edinburgh Handedness Inventory (Oldfield, 1971). These participants were different from Experiment 1.

Experimental Set-up and Instruments

The experimental set-up and instruments were identical to Experiment 1 except for the following. Only two ball-drop heights (2.4 m and 4.4 m), two electromagnetic solenoid devices (ball holders), and only a 6.5 cm diameter ball were used in this experiment.

Procedures

At the beginning of a test session, participants were given the handedness questionnaire, right-handedness was confirmed, and they signed an informed consent. Two FASTRACK sensors were attached on the nail surface of the index finger and thumb. The contact point of the right hand was aligned directly perpendicular to the ball-drop's path. As participants were placed on the experimental apparatus, participants wore liquid crystal display goggles throughout testing. In the monocular viewing condition, the left side of the goggle lens was blocked with a black plastic patch. In the binocular viewing condition, both sides of the goggles opened simultaneously. In the darkroom condition, only the luminescent ball was visible, but in the full-lighted condition, the ball and background information stimuli were clearly visible.

To start a trial, participants received a ready signal (a light touch on their left shoulder), 1 to 3 s later the shutters of the goggles were opened, and 500 ms later the ball was released by the electromagnet. The foreperiods between the ready signal and shutter opening of the goggles were randomly varied from 1 to 3s to reduce the possibility of anticipatory movements. To maintain the constant time period of 500 ms between shutter opening and ball release, an adjustable time delay switch was used.

To minimize any possible sound cues from the switch operation, participants wore earphones and heard low level white noise. Participants had no eye movement restrictions once the goggles were opened and they were instructed to catch the dropping ball as accurately as possible. The index finger and thumb were closed before ball-release to assume the ready position. To familiarize the participants with the experimental setting and task in each condition before testing began, 5 practice trials were provided. Fifteen trials were completed for each condition, and a total of 120 trials were administered. Eight different conditions (two ball-drop heights, two vision conditions, and two environment conditions) were presented randomly. After 30 trials, participants were given 3 min of rest. A detailed graphical illustration of the procedures is shown in Appendix E.

Dependent Measures

The number of successful ball catches was used as one index of performance score. The kinematics of the catching hand (index finger and thumb) movement were calculated and represented a second index. Specifically, the exact moment of ball and hand contact was determined by the ball contact switch on the center of the palm. All timing measures were defined with respect to the catching moment of ball contact with

the switch in the palm of the hand. Therefore, a negative time indicated the elapsed time before the ball was caught. A positive time indicated the elapsed time after the ball was caught (ball-palm switch contact). Seven dependent measures were defined:

- (1) Number of successful ball catches: the successful ball catches were calculated on 15 total trials in each condition.
- (2) Moment of opening (ms): the initiation time for opening (spreading a motion) the index finger and thumb relative to the instant of ball and hand contact.
Onset time of the opening was measured from the point at which the relative velocity changed to a positive value of index finger and thumb movements.
- (3) Maximum aperture size (cm): the maximum distance between the index finger and thumb prior to catching the ball.
- (4) Peak opening velocity (cm/s): the peak relative velocity of the rate of increase as the index finger and thumb are opened to maximum aperture.
- (5) Moment of closing (ms): the initiation time for closing the index finger and thumb relative to the instant of ball and hand contact. Onset time of this closing motion (grasp) was measured from the point that the index finger and thumb relative velocity changed to a negative value.
- (6) Peak closing velocity (cm/s): the peak relative velocity of the rate of decrease in aperture while the hand is readying for a catch (grasp).
- (7) Moment of ball catch (ms): the moment of ball catch by the index finger and thumb. Time to ball catch was measured from the point at which the relative velocity changed from a negative to a positive value of the index finger and thumb movements.

Results

Means and standard deviations were calculated for each dependent variable. The experimental design was a $2 \times 2 \times 2$ (Vision: monocular and binocular \times Ball Drop Height: 2.4 m and 4.4 m \times Environment: full light and dark) separate multivariate analysis of variance (MANOVA) with repeated measures on the three factors. All significant MANOVA effects were further analyzed in separate $2 \times 2 \times 2$ (Ball Drop Heights: 2.4 m and 4.4 m \times Vision: monocular and binocular \times Environment: full light and dark) univariate ANOVA with repeated measures on each factor. Alpha was set at .05 for all statistical analyses.

MANOVA results revealed three significant main effects for (a) vision, $F(6,4) = 27.1$, $p < .001$, Wilks' Lambda = 0.01672, (b) ball drop height, $F(6,4) = 9.71$, $p < .01$, Wilks' Lambda = 0.05832, and (c) environment, $F(6,4) = 8.36$, $p < .05$, Wilks' Lambda = 0.06945. There were no significant interactions among the three factors. Furthermore, MANOVA results for the mean standard deviation of dependent measures showed significant effects for both vision, $F(6,4) = 6.42$, $p < .05$, Wilks' Lambda = 0.06732, and environment, $F(6,4) = 7.33$, $p < .05$, Wilks' Lambda = 0.06125. No other significant effects were found among the three factors.

Catching Performance: Number of Successful Ball Catches

The means and the standard deviations of the number of successful catches are shown in Table 3.1. The catching performance appeared to improve with the additional source of visual information and this was confirmed by a significant vision main effect, $F(1,9) = 11.36$, $p < .001$. In the binocular vision condition, participants caught two more balls than during the monocular vision condition.

The environment condition revealed significant differences in catching performance, $F(1,9) = 10.98$, $p < .001$. Three more balls were caught in the illuminated environment condition than that in the dark environment condition. Figure 3.1, 3.2, and 3.3 show graphic representations of the results. No other significant main effect or interactions were found.

Table 3.1 Means and standard deviations for the catching performance as a function of ball drop height, vision, and environment.

	2.4 m		4.4 m	
	Binocular <u>M (SD)</u>	Monocular <u>M (SD)</u>	Binocular <u>M (SD)</u>	Monocular <u>M (SD)</u>
Light	11.7 (1.3)	9.6 (1.1)	10.8 (1.3)	8.5 (1.9)
Dark	8.8 (1.8)	6.3 (2.1)	7.7 (2.2)	5.5 (3.1)

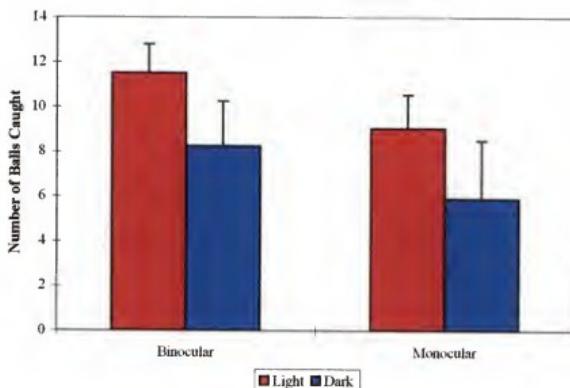


Figure 3.1 Means and standard deviation bars for the catching performance as a function of vision and environment.

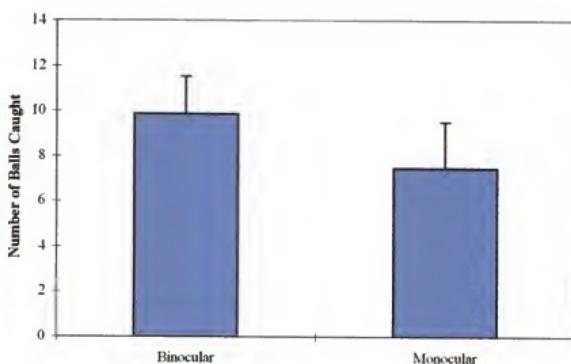


Figure 3.2 Means and standard deviation bars for the catching performance as a function of the vision main effect.

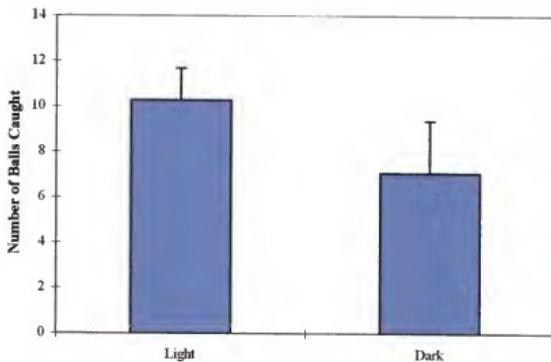


Figure 3.3 Means and standard deviation bars for the catching performance as a function of the environment main effect.

Moment of Opening

Table 3.2 depicts the means and the standard deviations for the moment of opening the index finger and thumb movements. As shown in the Table and Figure 3.5, the moment of opening started earlier in the monocular vision condition than in the binocular vision condition, $F(1,9) = 21.33$, $p < .001$. Furthermore, the moment of opening started earlier in the dark environment condition than in the lighted environment, $F(1,9) = 9.27$, $p < .01$. Figure 3.2.3 depicts a graphical representation of the environment effect. No significant effect for the ball drop height dependent measure or any interactions were found.

Additionally, the monocular vision condition showed higher variable timing performance for the moment of opening than the binocular vision condition, $F(1,9) = 10.62$, $p < .01$. In the dark environment, participants showed higher variability in the

moment of opening the hand than the lighted environment, $F(1,9) = 13.35$, $p < .01$. Figure 3.6 displays the results.

Table 3.2. Means and standard deviations for the moment of opening (ms) as a function of ball drop height, vision, and environment.

	2.4 m		4.4 m	
	Binocular M (SD)	Monocular M (SD)	Binocular M (SD)	Monocular M (SD)
Light	-258 (44)	-273 (68)	-260 (41)	-282 (71)
Dark	-279 (57)	-294 (86)	-272 (68)	-285 (88)

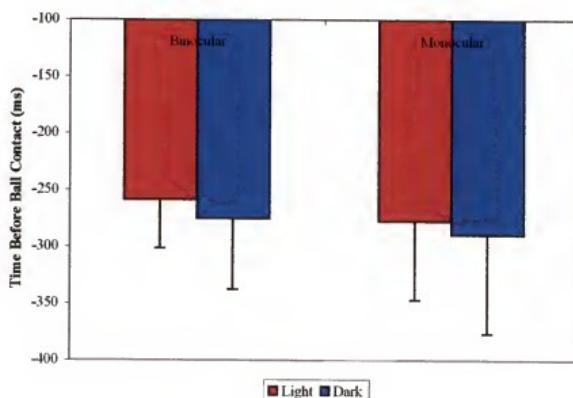


Figure 3.4 Means and standard deviation bars for the moment of opening as a function of vision and environment.

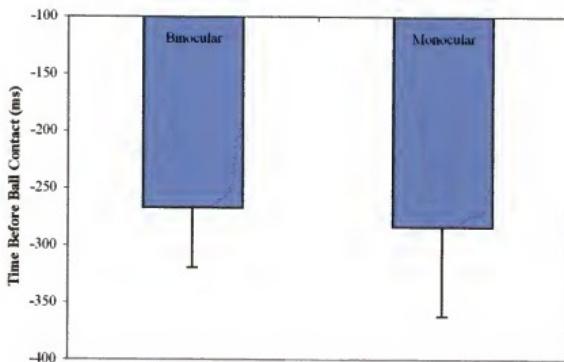


Figure 3.5 Means and standard deviation bars for the moment of opening as a function of the vision main effect.

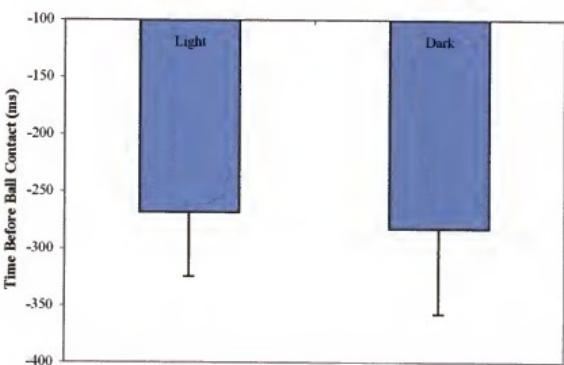


Figure 3.6 Means and standard deviation bars for the moment of opening as a function of the environment main effect.

Maximum Aperture Size

The maximum aperture size varied across the vision condition, $F(1,9) = 9.32$, $p < .01$ (see Table 3.3 and Figure 3.8). With the binocular vision, participants demonstrated a smaller aperture size than for the monocular vision condition.

Further, the maximal aperture size decreased with the illuminated environment compared with the dark environment condition, resulting in a significant environment main effect, $F(1,9) = 9.87$, $p < .01$. See Figure 3.9 for a graphical representation of this effect. These findings indicated that the maximum aperture size varied when other sources of visual information from the binocular vision and illuminated environment conditions were manipulated.

No significant main effect for ball drop height or interaction were found. Additionally, the mean standard deviation for the maximum aperture size failed significance for three of the main effects and four interaction terms.

Table 3.3 Means and standard deviations for the maximal aperture size (cm) as a function of ball drop height, vision, and environment.

	2.4 m		4.4 m	
	Binocular <i>M</i> (<i>SD</i>)	Monocular <i>M</i> (<i>SD</i>)	Binocular <i>M</i> (<i>SD</i>)	Monocular <i>M</i> (<i>SD</i>)
Light	10.32 (1.59)	11.06 (1.59)	10.67 (1.76)	11.37 (1.42)
Dark	10.98 (1.85)	11.72 (1.66)	10.92 (1.09)	11.85 (1.34)

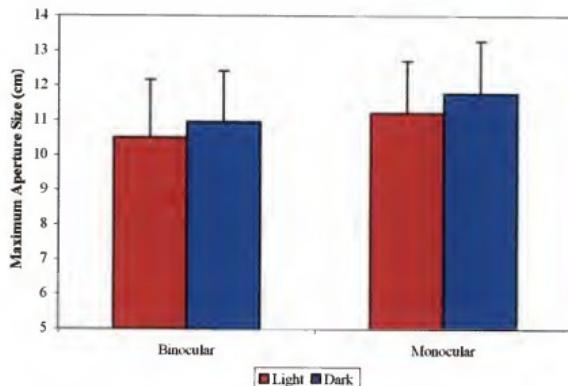


Figure 3.7 Means and standard deviation bars for the maximum aperture size as a function of vision and environment.

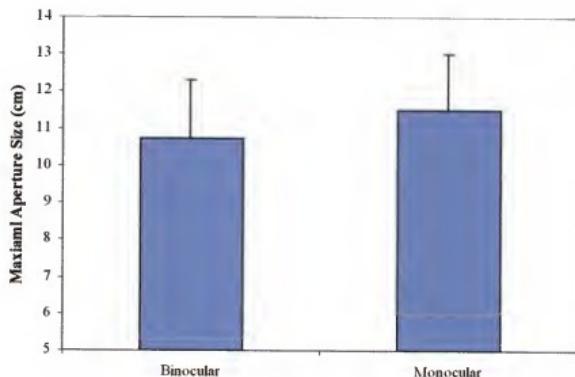


Figure 3.8 Means and standard deviation bars for the maximum aperture size as a function of the vision main effect.

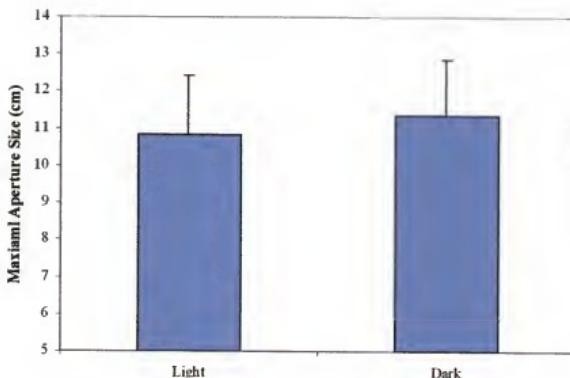


Figure 3.9 Means and standard deviation bars for the maximum aperture size as a function of the environment main effect.

Peak Opening Velocity

The means and the standard deviations for peak opening velocity of the index finger and thumb movements are shown in Table 3.4 and Figure 3.10. The peak opening velocity decreased with binocular vision and an illuminated environment, resulting in significant main effects for vision, $F(1,9) = 10.59$, $p < .01$, and environment, $F(1,9) = 9.12$, $p < .01$ (see Figure 3.11 and 3.12 for results). Further, the peak opening velocity increased with the higher ball drop height, $F(1,9) = 21.35$, $p < .001$. Additionally, analysis of the mean standard deviations of the peak opening velocity revealed that the binocular vision condition showed less variability of the peak opening velocity than the monocular vision condition, $F(1,9) = 5.21$, $p < .05$. Further, the illuminated environment condition exhibited less variability of the peak opening velocity than the dark environment, $F(1,9) = 7.26$,

$p < .05$. Neither the ball drop height standard deviations or interaction terms were not differentiated.

Table 3.4 Means and standard deviations for the peak opening velocity (cm/sec) as a function of ball drop height, vision, and environment.

	2.4 m		4.4 m	
	Binocular <u>M (SD)</u>	Monocular <u>M (SD)</u>	Binocular <u>M (SD)</u>	Monocular <u>M (SD)</u>
Light	47 (8)	58 (10)	65 (6)	76 (14)
Dark	52 (14)	61 (18)	66 (10)	87 (18)

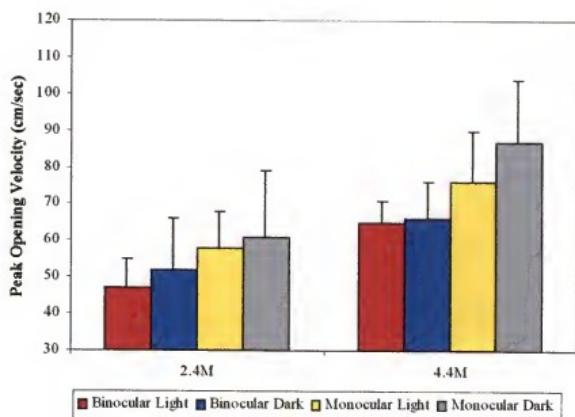


Figure 3.10 Means and standard deviation bars for the peak opening velocity as a function of ball drop height, vision, and environment.

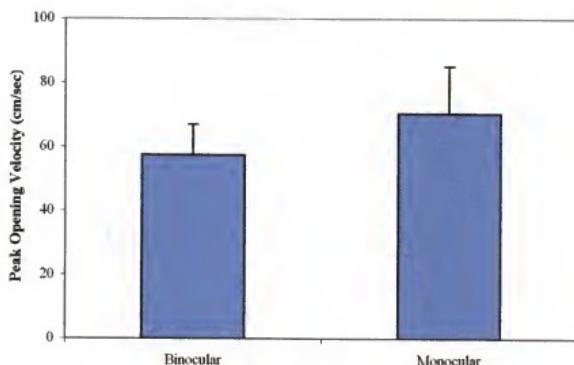


Figure 3.11 Means and standard deviation bars for the peak opening velocity as a function of the vision main effect.

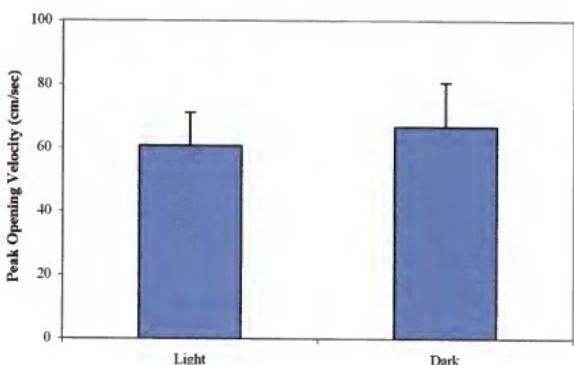


Figure 3.12 Means and standard deviation bars for the peak opening velocity as a function of the environment main effect.

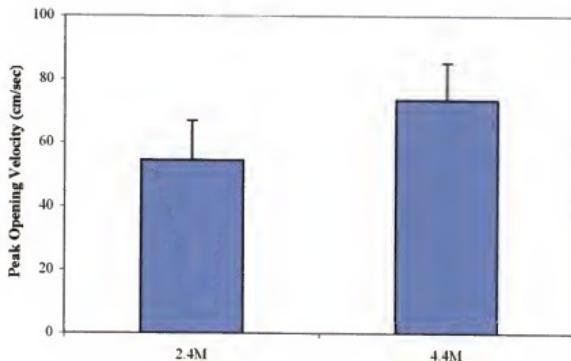


Figure 3.13 Means and standard deviation bars for the peak opening velocity as a function of the ball drop height main effect.

Moment of Closing

The means and the standard deviations for the moment of closing the index finger and thumb action are listed in Table 3.5. Binocular vision showed an earlier start of the moment of closing than monocular vision, $F(1,9) = 46.25$, $p < .001$ (Figure 3.15). Further, the illuminated environment produced an earlier start than the dark environment, $F(1,9) = 23.12$, $p < .001$ (Figure 3.16). The results showed that the moment of closing varied from the monocular vision and dark environment condition, indicating the moment of closing was changed by other sources of visual information. No significant main effects for ball drop height and interactions were found. The mean standard deviation for the moment of closing failed significance for main effects and interactions.

Table 3.5 Means and standard deviations for the moment of closing (ms) as a function of ball drop height, vision, and environment.

	2.4 m		4.4 m	
	Binocular M (SD)	Monocular M (SD)	Binocular M (SD)	Monocular M (SD)
Light	-56 (13)	-36 (09)	-57 (11)	-35 (13)
Dark	-55 (10)	-33 (10)	-48 (08)	-30 (09)

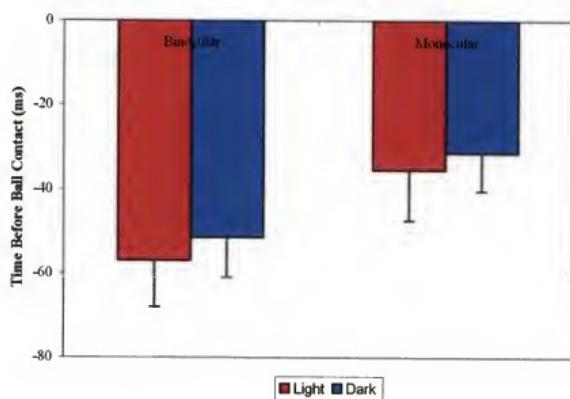


Figure 3.5.1. Means and standard deviation bars for the moment of closing as a function of vision and environment.

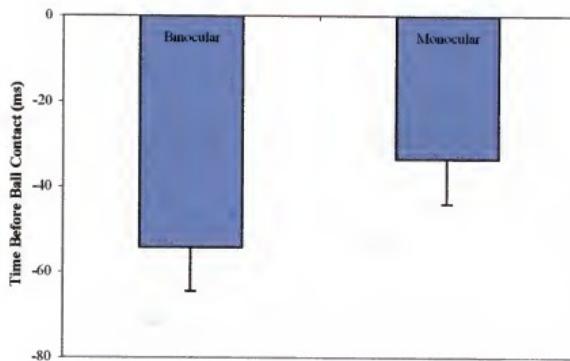


Figure 3.15 Means and standard deviation bars for the moment of closing as a function of a main effect (vision).

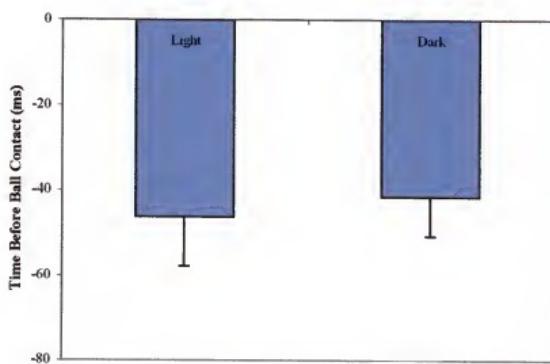


Figure 3.16 Means and standard deviation bars for the moment of closing as a function of a main effect (environment).

Peak Closing Velocity

The repeated measures analysis revealed that a significant ball drop height main effect was found, $F(1,9) = 42.16$, $p < .001$. The higher ball drop (4.4 m) resulted in a higher peak closing velocity than the lower ball drop (2.4 m). In addition, analysis of the vision condition indicated a significant main effect, $F(1,9) = 44.94$, $p < .001$. The binocular vision condition yielded lower peak closing velocity than the monocular vision condition. No other significant main effects or interactions were found. Additionally, no significant main effects or interactions for the mean standard deviation were found.

Table 3.6 Means and standard deviations for the peak closing velocity (cm/sec) as a function of ball drop height, vision, and environment.

	2.4 m		4.4 m	
	Binocular <u>M (SD)</u>	Monocular <u>M (SD)</u>	Binocular <u>M (SD)</u>	Monocular <u>M (SD)</u>
Light	-40 (10)	-43 (9)	-49 (12)	-51 (8)
Dark	-40 (11)	-45 (10)	-46 (11)	-57 (9)

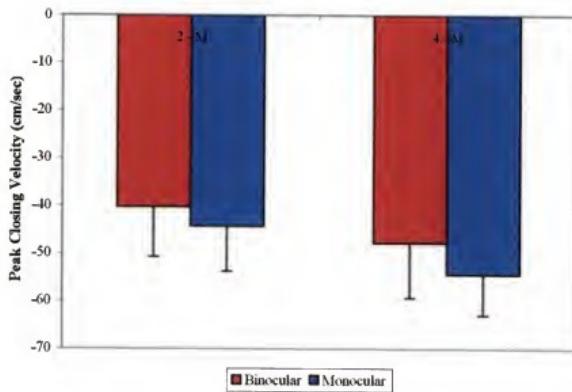


Figure 3.17 Means and standard deviation bars for the peak closing velocity as a function of ball drop height and vision.

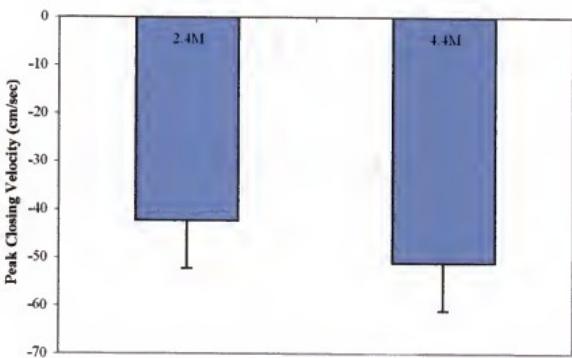


Figure 3.18 Means and standard deviation bars for the peak closing velocity as a function of the ball drop height main effect.

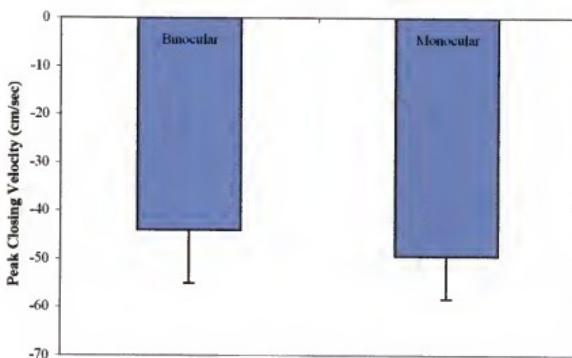


Figure 3.19 Means and standard deviation bars for the peak closing velocity as a function of the vision main effect.

Moment of Ball Catch

The univariate repeated measure analysis revealed that a significant ball drop height main effect was found, $F(1,9) = 7.67$, $p < .05$ (Figure 3.21). The higher ball drop (4.4 m) catch was completed earlier than the lower ball drop (2.4 m). More importantly, the binocular vision condition was completed earlier than that in the monocular vision condition, delivering a significant main effect for vision, $F(1,9) = 50.45$, $p < .001$ (Figure 3.22). Additionally, the main effects and the interactions for the mean standard deviations of moment of ball catch did not reach a significant level.

Table 3.7 Means and standard deviations for the moment of ball catch (ms) as a function of ball drop height, vision, and environment.

	2.4 m		4.4 m	
	Binocular <u>M (SD)</u>	Monocular <u>M (SD)</u>	Binocular <u>M (SD)</u>	Monocular <u>M (SD)</u>
Light	133 (6)	143 (8)	128 (6)	140 (9)
Dark	135 (6)	145 (12)	126 (5)	138 (6)

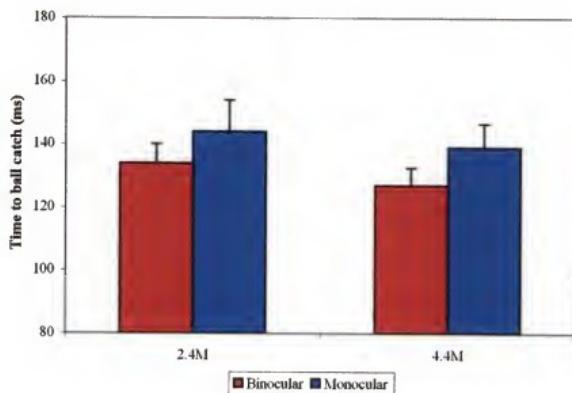


Figure 3.20 Means and standard deviation bars for the moment of ball catch as a function of ball drop height and vision.

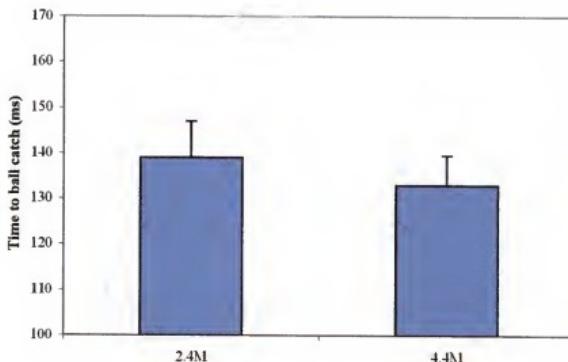


Figure 3.21 Means and standard deviation bars for the moment of ball catch as a function of a main effect (ball drop height).

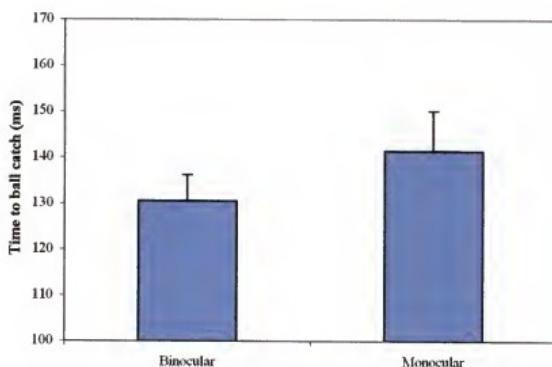


Figure 3.22 Means and standard deviation bars for the moment of ball catch as a function of a main effect (vision).

Discussion

The aim of Experiment 2 was to investigate the relative importance of vision (binocular versus monocular vision) and environmental constraints (illuminated versus totally dark) in regulating the interceptive timing of one-handed catching kinematic characteristics of an object falling with a constant acceleration due to gravity. The question of this study was whether the timing of one-handed catching was influenced by additional sources of visual information from the binocular vision or an illuminated environment.

Catching performance as indicated by the number of successful catches and kinematic measures of the index finger and thumb action during the one-handed catching were expected to be the same if interceptive timing of the one-handed catching was controlled with a tau strategy. The findings of catching performance indicated a higher number of ball catches under the binocular viewing condition. This finding was consistent with previous studies (Judge & Bradford, 1988; Savelsbergh & Whiting, 1992; von Hofstein et al., 1992), indicating that the binocular vision benefited from disparity (depth perception) for the dynamic interceptive timing task.

However, previous studies (Judge & Bradford, 1988; Savelsbergh & Whiting, 1992; von Hofstein et al., 1992) failed to decouple both spatial and temporal errors because the one-handed catching tasks involved uncertain spatial and temporal requirement. In Experiment 2, spatial uncertainty was eliminated because of the fixed hand position. Therefore, any errors in catching performance should be substantially derived from the temporal error of the index finger and thumb movements.

The kinematic analysis findings for the monocular vision condition showed (a) a later moment of opening, closing, and ball catch phase, (b) a higher peak opening and closing velocity, and (c) a larger maximum aperture size than the binocular vision condition. These findings indicate that monocular vision overestimated time-to-contact information of the approaching ball, and perceived an approaching ball faster than binocular vision. Furthermore, the larger maximum aperture size in the monocular vision condition may have been a consequence of the faster perception from the approaching ball. Additionally, the mean standard deviation of the moment of opening condition, and opening peak velocity for monocular vision showed larger variability than in the binocular vision. This was interpreted as a more stable pattern of index finger and thumb movement in the opening phase during binocular vision.

These results confirm previous interceptive timing findings (Bennett et al., 1999; Judge & Bradford, 1988; von Hofstein et al., 1992; Wann & Rushton, 1995). For example, in an one-handed ball catching task, Judge and Bradford (1988) increased the interocular separation by means of a telestereoscope. This manipulation biases depth perception by making the ball appear closer to the participants than it really is without affecting monocular cues such as the optical expansion pattern (τ). They reported that participants systematically closed their hands earlier when wearing the telestereoscope.

Further, Bennett et al. (1999) used a telestereoscope in a catching task with the hand in a fixed position. They found that telestereoscopic vision significantly affected the temporal characteristics of the ball catching. The index finger and thumb were closed earlier when depth perception was manipulated by making the ball appear closer. The present findings were congruent with these findings, suggesting that disparity (depth)

information from binocular vision affects the timing control pattern of the index finger and thumb action for catching a ball.

In addition, the kinematic patterns of the index finger and thumb movements in the binocular vision identified less timing error for the opening phase (i.e., less variability of moment of opening and peak opening velocity) and later completion of the ball catch. These findings suggest that the more successful catches for binocular vision might be the result of more consistent timing and velocity control of opening the index finger and thumb movements. Further, the less successful ball catch in monocular vision might be derived from an earlier completion of the ball catch than in the binocular vision.

Similar results were reported by Sharp and Whiting (1974). They found that the 240-300 ms before ball contact is a critical component of visual information. During this interval, visual input should be accurate and stable for a successful ball catch. The current results indicate a binocular advantage during the opening phase period, and participants received a benefit from disparity (depth) with more accurate and consistent timing control during the ball catching action.

Concerning the environmental effect, findings showed that the catching performance scores were significantly better in the illuminated environment than in the totally dark environment. The kinematic analysis revealed more timing error (i.e., higher variability) in the dark environment for the moment of opening and peak opening velocity. Further, the earlier moment of opening, the higher peak opening velocity, and the larger maximal aperture size were found in a totally dark environment than in the illuminated environment. These results were interpreted as beneficial effect from an illuminated environment, which changed the perception of the approaching ball and

affected the timing pattern (the more consistent timing pattern ball catching action) as well as the catching performance (the higher number of successful catches).

The current findings are consistent with Rosengren et al.(1988) and Savelsbergh and Whiting (1988). Both studies reported an enhanced effect of the illuminated environment for temporal accuracy when compared to the dark environment with only a luminous ball visible. From an ecological perspective, if tau provides necessary and sufficient timing control information, the ball catching performance in the totally dark environment should provide the same quality of performance and timing patterns of index finger and thumb movement in illuminated environment. However, the current study yielded better catching performance, less timing error, and a later moment of opening in the illuminated environment than in the dark environment.

From the current results, a question should be addressed concerning why an illuminated environment enhances performance and affects the timing patterns of the catching action. One possible explanation is that the greater contrast between the ball and the environment caused a misperception of the approaching ball velocity. That is, the ball may appear to move faster and closer to the participants in the totally dark environment. Thus, the earlier moment of opening with a larger maximal aperture and a higher peak opening velocity in the totally dark environment may reflect a misperception of ball distance and approaching velocity (Koslow, 1985). Moreover, Wing, Turton, and Fraser (1986) required participants to reach and grasp a stationary target while approaching it at different velocities and found that the maximal aperture size and the peak opening velocity were increased significantly with the faster approach velocity. The authors' explanation focused on how participants tried to increase contact possibilities with the

object by increasing their maximal aperture size and opening velocity. Consequently, in the totally dark environment, the earlier moment of opening, the larger maximal aperture, and the higher opening velocity might be due to the participants' misperceptions (i.e., perceiving a approaching ball faster and closer).

A second explanation for the current empirical findings is that two kinds of time-to-contact information are simultaneously available in the illuminated environment. One source is specified by the relative rate of optical expansion while the ball is approaching participants. The other is specified by an algorithmic computation based on information about ball size and distance prior to ball drop because participants can easily extract precise distance and size information prior to the actual ball drop. In the totally dark environment, participants received the timing information from only a relative rate of optical expansion from the approaching ball. However, in the illuminated environment, participants may receive some benefit from the prior perceived estimate of distance and ball size information before the ball is released. The current results indicated that the increased variability of the moment of opening, closing, and peak opening velocity in the dark environment may be a consequence of the unavailability of prior estimates about the distance and ball size information for pre-calibration or programming of the interceptive timing action. Such a situation would produce less accurate (fewer successful) catches as well as a less consistent pattern of the catching action.

In conclusion, the altered timing patterns of index finger and thumb movements, the less variability of opening phase, and the improved successful catching performances indicated that the interceptive timing action was affected by the illuminated environment and binocular vision condition. This conclusion was drawn based on similar previous

studies as well as the difference between relative disparity and absolute disparity. The current findings present evidence that tau is not the only source for controlling the interceptive timing action. This evidence clearly suggests that participants used multiple sources of visual information when available to achieve more accurate and consistent task performance.

CHAPTER 4 GENERAL DISCUSSION

Experiments 1 and 2 were designed to investigate the expansion rate of the approaching image (τ_{au}) during the interceptive task for catching a ball. The findings of Experiment 1 strongly suggest that the interceptive timing information can be provided by the optical expansion rate of an approaching ball (Gibson, 1979, Lee, et al., 1983; Savelsbergh et al., 1991, 1993). The kinematic analysis revealed that the moment of closing the index finger and thumb action did not change across the different ball sizes or ball drop heights. The size difference between the large and small ball size (1 cm) was reflected in the 1 cm difference of the maximal aperture size. The peak opening and closing velocity was coupled with different approaching ball speed because of the different ball drop heights. The current findings support the notion that the changing optical image size on the retina from an approaching ball can provide accurate timing information for ball catching. Participants were able to pick up the accurate time-to-contact estimate from the dropping ball. Consequently, participants were able to adjust their aperture size to the different ball sizes and start the closing of the index finger and thumb action at a constant moment (Experiment 1: the moment of closing was 36 ms before ball-hand contact).

In addition, the variability score of the moment of the index finger and thumb action decreased when compared with the opening, closing around the ball, and catch phases. Specifically, the interceptive timing for ball catching at the moment of opening

may be less accurate and consistent, showing larger variability (± 35 ms). However, as the moment of closing and catching approached, the variability in the catching hand decreased dramatically (± 10 ms). These findings indicate that the catching index finger and thumb action was not predetermined or preprogrammed, but continuously tuned and adjusted up to the final phase of catching (Bootsma, et al., 1992, Schmidt & Lee, 1998).

Although researchers argued that the relative rate of optical expansion is used to control the interceptive timing action (Lee et al., 1983; Savelsbergh et al., 1991, 1993), binocular vision and/or environmental structure enhanced catching performance for the interceptive actions. There has been equivocality regarding the reliance of monocular information alone (Regan, 1997). Recently, detailed kinematic analyses have revealed that the differences of timing patterns for interceptive timing movements between monocular and binocular vision, with or without environmental structure (e.g., given that both the illuminated environment and background information were available) were not consistent with the concept of tau (Bennet et al., 1999; Scott et al., 1997; van der Kamp et al., 1997; Wann & Rushton, 1995). In particular, the previous findings indicate that tau is not the only variable that contributes to the act of specifying the time-to-contact. The multiple sources of visual information may affect the interceptive timing action (Heuer 1993; Laurent et al., 1996; Regan, 1997; Tresilian, 1990, 1994). These findings indicated that the optical variable tau may be only used in a limited condition (i.e., only optically expanding the image of approaching or dropping ball available because of monocular vision and dark environment).

The purpose of Experiment 2 was to determine whether the interceptive timing action is affected by different multiple sources of visual information such as binocular

vision and illuminated environment. The current findings of Experiment 2 showed the beneficial effects on binocular vision and an illuminated environment. Clear evidence suggests that when examining the number of successful catches, binocular vision (disparity), and illuminated environment (relative distance perception due to the fixed distance information such as ceiling surface or horizontal ball drop bar) conditions enhance catching performance. The temporal characteristics of the index finger and thumb catching action demonstrate that the interceptive timing actions were performed differently under the binocular vision and/or illuminated environment comparing with a constant time-to-contact strategy. Furthermore, under binocular vision and/or the illuminated environment, the variability of timing and peak velocity values for opening and closing the hand were significantly decreased. These current findings of binocular vision are consistent with recent findings reported by Bennett et al.(2000).

Given that in their study, binocular vision altered the aperture size and timing of index finger and thumb movement comparing with monocular vision. The current results are interpreted that the relative rate of expansion cannot exclusively explain the timing of the ball catch. Using multiple sources visual information for more accurate and consistent control of interceptive timing action is emerging from the current results. The questions about how or when these multiple sources of visual information are used should to be addressed in future studies.

One possible explanation about multiple sources of visual information affecting interceptive timing was proposed by Tresilian (1994). In his model, various visual sources of information are obtained from different visual information sources and evaluated. In this evaluation process, the available information sources are differentially

weighted and combined (e.g., summing up and/or multiplying the information sources), resulting in a time-to-contact estimate. For example, there are less competing information sources in the monocular vision and totally dark environment under such a circumstance. Tau would be the most important visual information source. Consequently, interceptive timing control would be dependent on the relative rate of optical image size expansion. The present findings in both Experiments 1 and 2 in the condition of monocular vision and totally dark environment support this explanation. The moment of the index finger and thumb movements started at a constant time-to-contact (moment of closing). However, if more than one source of visual information from binocular vision (disparity) or an illuminated environment (relative distance perception) is available, a different evaluation principle may be used.

Concerning the possibility of using multiple sources of visual information, Davids et al. (1994) argued that the human motor control system has a considerable amount of redundancy. Redundancy forms an integral aspect of the flexible human performance system that ensures that the perceptual and motor control system functions efficiently. Thus, the alternative control systems such as cognitive and ecological systems may permit the performer to cope with severe temporal and spatial demands simultaneously depending on task constraints.

Rushton and Wann (1999) provided a weighted combination of size and disparity information model for interceptive timing (tennis ball catching task) based on a virtual reality task. The looming condition (providing only optical image change of an approaching ball) showed higher timing error and later moment of closing (i.e., grasp) than the combined condition with ball size and disparity information, suggesting that the

combined multiple source of visual information changed the timing pattern (an earlier start) with more accurate interceptive timing performance.

Further, Button et al. (2000) examined the kinematics of ball catching in skilled catcher when mechanical perturbation of catching arm was expected and unexpected. The results showed that during trials where the perturbation was anticipated, participants initiated movements earlier (207 ± 32 ms) than in randomly perturbed trials (223 ± 34 ms). Furthermore, participants tended to move their hand faster when perturbations were expected compared to baseline trials. Anticipatory responses were revealed in changes not only at movement initiation but also in resulting adaptation to the co-ordination of reach and grasp phases of ball catching. When the participants could not anticipate perturbations, movement strategies were a continuous tracking-based mode of control rather than a prediction-based mode of control. These findings are supportive evidences of two possible mode of control strategy.

The current results of Experiment 2 provide supportive evidence favoring these proposed models. The improved catching performance, the changed kinematic patterns, and the more accurate kinematic patterns indicate that these improved timing actions are facilitated by the benefit of multiple sources of visual information.

Further, concerning recent neurophysiological and neuropsychological evidences, two distinct independent visual systems, the dorsal and the ventral pathway constitute to the above explanation of these two systems (Goodale & Milner, 1992; Milner & Goodale, 1995). According to the independent distinction, the dorsal system picks up visual information more quickly than the ventral system without much involvement of conscious awareness. Thus, the dorsal system does not burden the cognitive system with

the task of interpreting the stimulus input, and the information pickup for performance of well-ingrained action or behavior is carried out by the dorsal system. In contrast, the ventral system primarily serves in recognition and identification of objects in one's environment. The ventral system compares visual inputs to stored information in a quest for a meaningful interpretation of those inputs (Goodale & Haffenden, 1998).

According to Creem and Proffitt (2001), when needed, the ventral system also participates in other perceptual activities, such as different aspects of space perception like the perception of object size and distance. In addition, Norman (in press) proposed a dual mode process based on the two visual systems. According to his proposition, the ecological approach broadly parallels the functions of dorsal system. In contrast, the cognitive approach broadly parallels the ventral system. As the dorsal system is mainly concerned with directing motor behavior in the environment, this system relies on 'body-centered' information, in absolute units, about the environment and objects. In contrast, the ventral system in its attempt to recognize objects can suffice with relative, 'object-centered' information (Wertheim, 1994). These functionally distinct two visual systems work together and/or independently, but the function might be dependent on the stimuli; (i.e., different types of visual information arising from the object) and responses (e.g., verbal report or actual catching or hitting) action constraints.

Findings from both Experiment 1 and 2 are consistent with Norman's argument. For Experiment 1, the results of the kinematic analysis of index finger and thumb action support the argument that under the monocular vision and the dark environment with only a luminous ball visible, when the index finger and thumb started to open and expanded to maximum aperture size, the timing of the ball catching action showed higher

variability in timing. However, higher variability of timing for the ball catching movement decreased as the ball approached the contact point with the right palm. That is, as the ball approaches closer, obtaining time-to-contact information becomes clearer. These results indicate that the interceptive timing action was not programmed based on the prior knowledge or visual information about ball and distance. Rather the reactive control strategy (i.e., tau) based on a continuously expanding optical image of the approaching ball appears to be primarily involved.

Along the same line, in Experiment 2, additional binocular vision and a fully lighted environment were available before the ball was released. Thus, participants were able to perceive accurate ball size and distance information 500 ms before a ball drop. Furthermore, even during the ball catching movement, the ongoing visual information about ball size, distance, and velocity changes may be much more abundant and precise in terms of the quality of visual information for the interceptive timing control. In this case, the cognitive-ventral system possibly took on a role for the task demand of interceptive timing control with the more accurate perceptual evaluation with a short period of time before and during the ball catching movements. Therefore, control for interceptive timing may achieve a prediction process or pre-determination process based on multiple sources of visual information prior to the ball catching (i.e., without optical expansion information). Furthermore, a recent neurocomputational model of working memory was proposed by Durstewitz et al. (2000) in which visual information about the object's location or direction initially triggers a neuronal network pool in the prefrontal cortex area and then maintains a continuous attractor state with a higher firing rate of their synaptic connection. This neurocomputational model of working memory supports

the notion that a pre-determination or calibration process can be achieved from location of the object brief periods of time as the ball approaches.

The results in Experiment 2 showed more consistent timing and velocity patterns (i.e., less variability in the moment of opening and peak opening velocity) for the opening phase of the hand. These results suggests that benefit may be given to participants from the process of precalculation or predetermination process before and during the opening phase of index finger and thumb movements. In contrast, the moment of closing and ball catch did not affect the timing variability. These findings tentatively suggest that when the additional multiple sources of visual information are available, the control of the opening phase of the catching motion may be mainly controlled by the cognitive-ventral system (i.e., predictive control or predetermination control mode). However, the control of the closing phase and the ball catch phase appears to be primarily controlled by the ecological-dorsal system (i.e., reactive control mode).

In conclusion, Experiment 1 findings support that the optical expansion rate of an approaching ball (τ) based on the ecological perspective was used as a control variable for interceptive timing task under the various ball drop heights and ball sizes. However, only providing optically expanding ball image is seldom in a real life situation. The findings of Experiment 2 showed that the binocular vision and the illuminated environment changed the ball catching performances and the kinematic patterns of the index finger and thumb movements for ball catching action with more consistency. These results indicated that multiple sources of visual information were used to achieve more accurate timing and more successful ball catches.

In summary, tau has been extensively used as a control variable for interceptive timing actions (Lee, 1976). However, recent studies have been reported inconsistent results with the tau hypothesis. First, the previous studies failed to control the input variables such as the optical image and expansion rate of the approaching ball. Thus, sources of visual information were confounded. Second, the previous studies failed to provide realistic responses. This caused difficulties in evaluating interceptive timing actions concerning whether the timing error derived from the input variables or the unrealistic responses.

The aim of Experiment 1 was to examine whether tau was used as a control variable source of visual information for interceptive timing actions while only providing the optical image of an approaching ball and a more realistic ball catching response in a gravitational acceleration context. The constrained one-handed ball catching task with different ball drop heights and ball sizes was tested in a totally dark room condition with only right eye monocular vision available. Thus participants only had an optical expansion image (tau) of the luminescent dropping ball. The results of Experiment 1 showed that ball catching action corresponded with tau prediction regardless of manipulation of ball drop heights and ball sizes.

However, seldom in catching is only an optical image of an approaching ball available. Experiment 2 provided binocular vision and an illuminated environment as additional sources of visual information. The findings revealed higher catching performance scores, and the index finger and thumb movements of the catching hand were more precise and consistent in the binocular and lighted condition. These findings suggest that a control system for interceptive timing actions uses the optical expansion

rate of an approaching ball to execute a ball catching action. In contrast, when other sources of visual information (binocular vision and/or illuminated environment) were provided the human control system uses these sources of visual information simultaneously to achieve a more accurate and consistent catching action.

Findings from both of Experiments 1 and 2 provide two possible control modes (i.e., reactive control mode and predictive control mode) for visual information processing. The reactive control mode is mainly involved with unpredictable conditions about ball size and distance as well as the ball's approaching speed. Meanwhile, the predictive control mode is mainly involved with a predictable condition before the ball catching action begins (Norman, *in press*). However, in a real life situation, it is difficult to dissociate two control modes to determine which mode is functioning. Based on current findings of Experiment 1, the reactive control mode appears to operate via a concurrent and continuous perception and action coupling process because of no prior visual information provided and only optical expansion of an approaching ball image is available. In Experiment 2, when additional sources of visual information were provided the findings showed higher successful ball catches, less variability, and an earlier start of the opening phase of ball catching action. Together these results indicate a beneficial effect from predictive control mode because of earlier detection of ball position and more accurate perception of the approaching ball with binocular vision in an illuminated environment.

Recently, integrated modeling approaches have been proposed to study of movement control and behavior (Williams, Davids, & Williams, 1999; Davids, Williams, Button, & Court, 2001). The arguments proposed in the integrated modeling approaches

were supported and strengthened by recent findings on neurophysiological basis of perception and action (Goodale & Humphrey, 1998; Harris & Jenkins, 1998; Milner & Goodale, 1995). In their studies, two distinct visual processing pathways within one visual system provided a possibility of integration from two different perspectives. The ventral pathway has associations with the related areas of memory, which may indicate the cognitive process on goal-directed behavior. The dorsal pathway is directly connected to motor areas of the brain, which is harmonious with the perception-action coupling route (Davids, et al., 2001). Therefore, the integrated modeling approach provides a framework of understanding the solution for stimulus specific conditions. The current findings are consistent with this integrated approach. Specifically, the dorsal pathway system mainly functions in a condition of only providing optically expanding ball image and the ventral pathway system mainly operates with binocular vision and an illuminated environment for interceptive timing actions. Future ball catching action studies should investigate integrated modeling questions to further explain behavior.

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APPENDIX A INFORMED CONSENT FORM

University of Florida
Motor Behavior Laboratory
Informed Consent

Protocol Title: Timing Control of One-Handed Catching: Ball Accelerating by Gravity
Please read this consent document carefully before you decide to participate in this study.

Purpose:

The purpose is to examine the timing control of one-handed catching while a dropped ball accelerates by the gravity.

What you be asked to do in the study:

You will be asked to lay down to a flat board on the floor and to wear liquid crystal goggles. Your right hand will be positioned on direct ball drop line and your wrist will be fixed on wrist supporter. The task will be to catch a ball dropping from different heights. You will be three given practice trials on each ball height and ball size condition. Following the practice trials you will be asked to catch the dropping ball as accurately as possible. The goggles will open as soon as the ball is mechanically released (dropped). Depending on the experiment, you will catch the ball in either a monocular or binocular condition.

Time required:

Approximately 90 minutes.

Risks and Benefits:

Maintaining a steady wrist position during testing may cause a slight wrist pain. However, plenty of opportunities will be provided for full wrist rotation during testing (between trials). No direct benefits will be provided to you. However, this research is intended to advance our understanding of the tau response principle of human catching movements.

Compensation:

You will be given extra credit in your class for participating in this research.

Confidentiality:

Your identity will be kept confidential to the extent provided by law. Your information will be assigned a code number. The list connecting your name to this number will be kept in a locked file in my faculty supervisor's office. When the study is completed and the data have been analyzed, the list will be destroyed. Your name will not be used in any presentation or publication.

Voluntary participation and Right to withdraw from the study:

Your participation in this study is completely voluntary, and you have the right to withdraw from the study at anytime without consequence.

Whom to contact if you have questions about the study:

Sang-Bum Kim, Graduate Student, Department of Exercise and Sport Sciences, 132 FLG,
Phone: 352-213-2120. E-mail:sangbumk@ufl.edu

James Cauraugh, Associate Professor, Department of Exercise and Sport Sciences, 132
FLG, Phone: 392-0584 (ext) 1273. E-mail:jcaura@hhp.ufl.edu

Whom to contact about your rights as a research participant in the study:

UFIRB Office, Box 112250, University of Florida, Gainesville, FL 32611-2250
phone 392-0433.

Agreement:

I have read the procedure described above. I voluntarily agree to participate in this study
and I will receive a copy of this description if requested.

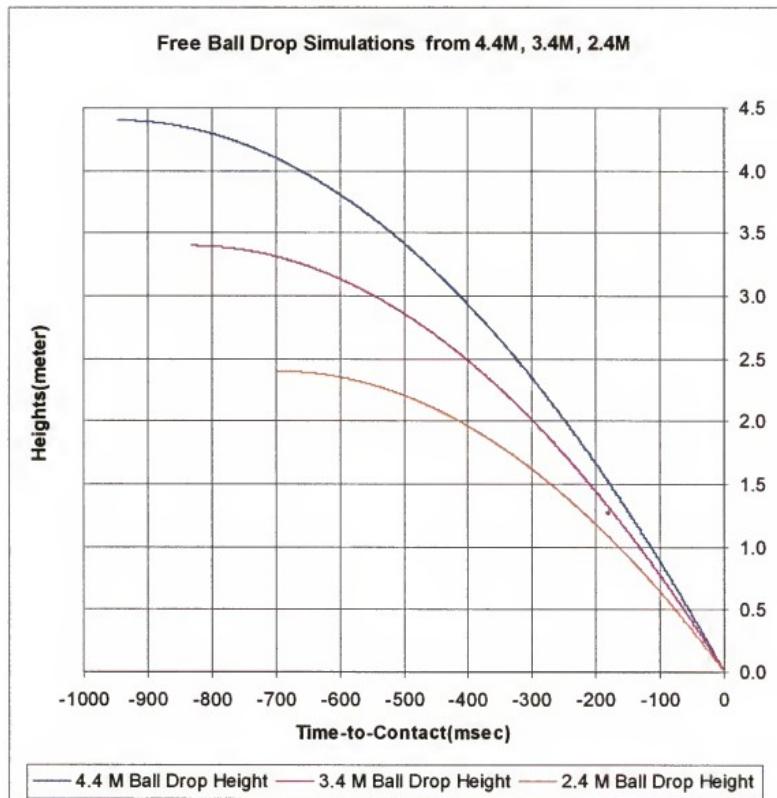
Participant: _____ Date: _____

Principal Investigator: _____ Date: _____

APPENDIX B
EXPERIMENTAL SET-UP AND INSTRUMENTATION

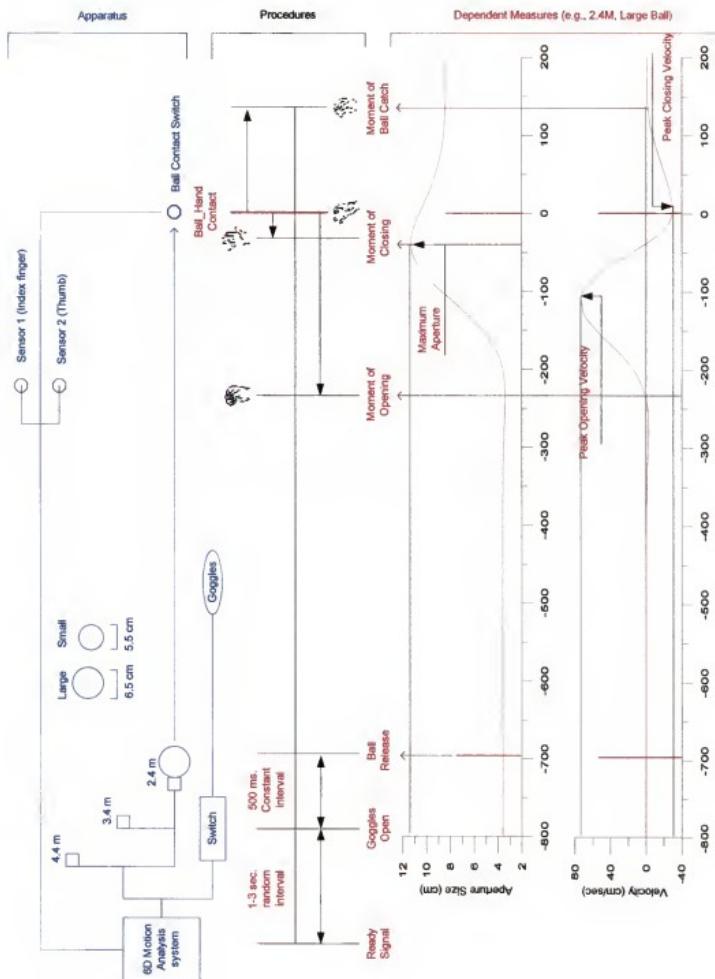


APPENDIX C
SIMULATED FREE BALL DROP



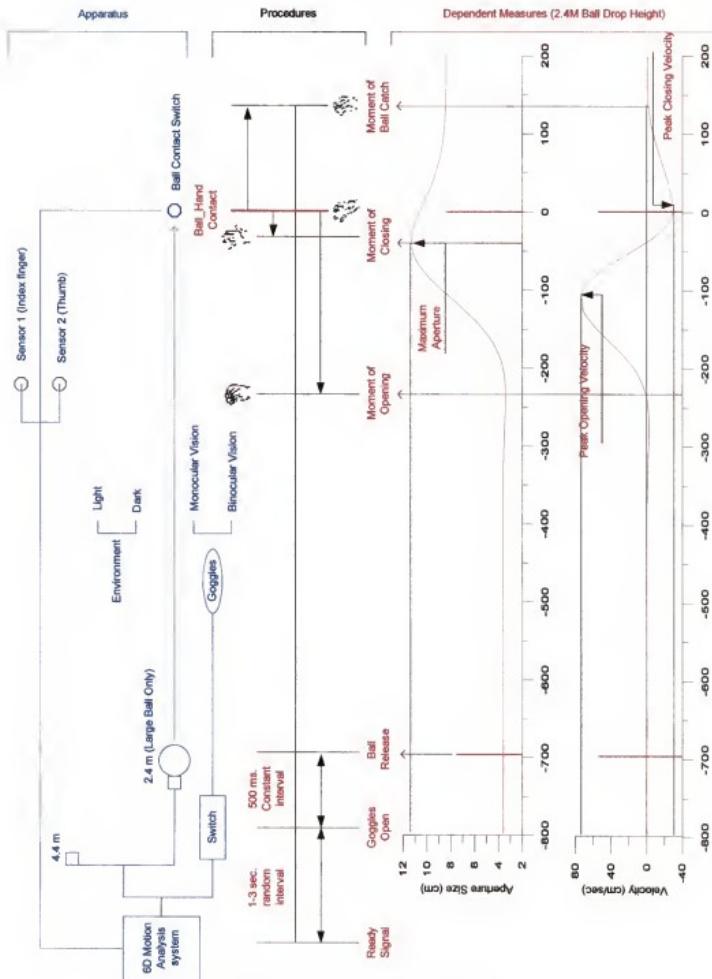
APPENDIX D

EXPERIMENT 1: SETTINGS AND PROCEDURES



APPENDIX E

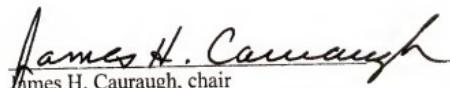
EXPERIMENT 2: SETTINGS AND PROCEDURES



BIOGRAPHICAL SKETCH

Born on June 25, 1966, in Namhae island, South Korea, Sang-Bum Kim was raised by his parents, Lee-II and Jung-Ja Kim. After graduating from Hak-Sung high school in Ulsan, Korea, Sang-Bum earned his Bachelor of Education degree from Seoul National University in 1989. He then continued to pursue his Master degree at Seoul National University, with the major in motor control and learning under the tutelage of Dr. Chung-Hee Chung. Upon completion of this degree, he enrolled in the College of Health and Human Performance at the University of Florida as a Ph.D. candidate in motor control and learning and was mentored by Dr. James H. Cauraugh. He completed his dissertation and awarded the Ph.D. degree in August 2002.

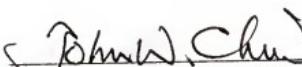
I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy in Health and Human Performance.


James H. Cauraugh, chair
Associate Professor of Exercise and Sport Sciences

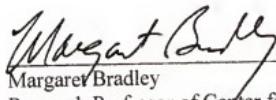
I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy in Health and Human Performance.


Robert N. Singer
Professor of Exercise and Sport Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy in Health and Human Performance.

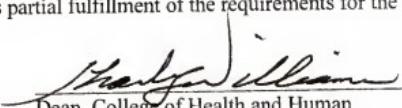

John Chow
Assistant Professor of Exercise and Sport Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy in Health and Human Performance.


Margaret Bradley
Research Professor of Center for the Study
of Emotion and Attention in National
Institute of Mental Health

This dissertation was submitted to the Graduate Faculty of the Department of Exercise and Sport Sciences, to the College of Health and Human Performance, and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy

August 2002



Marlyn Williams
Dean, College of Health and Human
Performance

Dean, Graduate School